ACOUSTIC,
RESPIRATORY KINEMATIC AND ELECTROMYOGRAPHIC
EFFECTS
OF
VOCAL TRAINING

By

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To my family, friends, and Portugal,
who are the inspiration of my life and my dreams.

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By

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The longitudinal effects of vocal training on the respiratory, phonatory and articulatory systems of voice majors were investigated in this study. During four semesters, fourteen voice major students were recorded while speaking and singing. Acoustic, temporal, respiratory kinematic and electromyographic parameters were measured to determine changes in the three systems as a function of vocal training. Acoustic measures of the speaking voice included fundamental frequency, sound pressure level (SPL), percent jitter and shimmer, and harmonic-to-noise ratio. Temporal measures included duration of sentences, diphthongs and the closure durations of stop consonants. Acoustic measures of the singing voice included fundamental frequency and sound pressure level of the phonational range, vibrato pulses per second, vibrato amplitude variation and the presence of the singer's formant.

Analysis of the data revealed that vocal training had a significant effect on the singing voice. Fundamental frequency and SPL of the 90% level and 90-10% of the phonational range increased significantly during four semesters of vocal training.

Physiological data were collected from four subjects during three semesters of vocal training. Respiratory kinematic measures included lung volume, rib cage and abdominal excursions extracted from spoken and sung samples. Descriptive statistics revealed that rib cage and abdominal excursions increased from the 1st to the 2nd semester and decrease from the 2nd to the 3rd semester of vocal training.

Electromyographic measures of the pectoralis major, rectus abdominis and external oblique muscles revealed that burst duration means decreased from the 1st to the 2nd semester and increased from the 2nd to the 3rd semester. Peak amplitude means increased from the 1st to the 2nd and decreased from the 2nd to the 3rd semesters of vocal training. Chest wall excursions and muscle force generation of the three muscles increased as the demanding level and the length of the phonatory tasks increased.

CHAPTER 1
INTRODUCTION AND REVIEW OF TERMS

Introduction

The human voice results from motor activity that is determined by genetic, linguistic, social and cultural factors. Its production involves a complex aerodynamic and biomechanic process that requires the neurophysiological coordination of three anatomical systems, i.e. the respiratory, laryngeal and supralaryngeal systems. The respiratory system, in concert with the larynx, generates the subglottal air pressures necessary to initiate and maintain voicing. The laryngeal system is the source of the vocalization and the supralaryngeal system modulates the energy produced by the source into an acoustic output that is perceived by the listener. These systems are used both in speaking and singing; however the singing voice requires maximizing the vocal output by increasing the coordination of respiration, phonation and resonance (Morrison & Rammage, 1994; Titze, 1994; Verdolini, 1998).

Due to maturation, physical and emotional growth, and, eventually, the aging process, the voice undergoes periodic changes. Normal and disordered voices have been the topic of various investigations. However, few have studied the optimal voice, the maximal voice, or even the changes that occur during vocal training. The few studies that have examined these issues have been comparisons between singers and nonsingers in the production of both speaking and singing voice. These studies report that differences exist between the two populations in perceptual, acoustic and physiologic parameters.

The speaking voices of singers and nonsingers have been compared in several different studies. The research literature concerning this topic includes areas of speaking fundamental frequency (Brown, Morris, Hollien, & Howell, 1991), sound pressure level (Åkerlund, Gramming, & Sundberg, 1992), perturbation measures (Brown, Morris, & Michel, 1990; Lieberman, 1961; Murry & Large, 1978), temporal measures (Rothman, Brown, Sapienza, & Morris 1998; Rothman, Brown, & Lafond, 1999), subglottal air pressure (Titze & Sundberg, 1992), intraoral breath pressure (Brown, Hunt, & Williams, 1988) and respiratory kinematics (Hixon, Goldman, & Mead, 1973).

The singing voice has also been the focus of several reports. These reports include areas of respiratory function in singers (Sataloff, 1988; Sundberg, 1990), respiratory kinematics (Hixon, 1991), subglottal pressure and airflow (Rothenberg, 1977; Sundberg, 1990), surface electromyographic measurements (Watson, Hoit, Lansing, & Hixon, 1989), phonation (Sundberg, 1990), acoustics (Sundberg, 1987; Titze, 1994), singer's formant (Hollien, 1983; Rothman & Timberlake, 1984; Sundberg, 1974), vibrato (Rothman, 1987) and articulation (Brown et al., 1988; Sundberg, 1990).

The combined results of the above studies have provided evidence that singers, when compared with nonsingers, use different physiological strategies for singing. It appears that vocal training and singing experience have an effect on the respiratory, phonatory, and articulatory systems, an effect that has been reflected in several different signals, such as, the respiratory kinematics, surface electromyographic and acoustic signals. Additional studies have concluded that singing efficiency, including maximizing vocal intensity, optimizing quality, and sustaining tones for long periods of time, is the result of vocal training and experience (Boone, 1988; Sabol, Lee, & Stemple, 1995; Leonardo, Ringel, Daniloff, & Horii 1987; Titze, 1979).

Vocal Training

Vocal training is defined as a process that a singer goes through in order to maximize vocal output through the coordination of respiration, phonation and resonance. Historically, many technical approaches have been used to achieve the ideal voice, often based on regional, national or international preferences (Verdolini, 1998). Vocal training focuses on at least four main areas; body and posture awareness, increasing breath support, isometric-isotonic vocal function exercises and articulatory production exercises.

Body and posture awareness is a traditional aspect of voice training. Voice production is essentially a physical event integrated into a whole-body system. Vocal training is mostly practiced in a standing position with particular attention on postural alignment. Singing teachers use not only self-awareness and kinesthetic sensitivity, but also body training exercises (Verdolini, 1998).

The airflow, generated by the respiratory system, is the power source of the singer's voice. Singers need to increase breath efficiency and control through the coordinated use of the inspiratory and expiratory muscles (Sataloff, 1998). Many of the strategies used in vocal training place a great deal of emphasis on the positioning of the abdominal wall in the singing act (Watson & Hixon, 1985). Knowledge of respiratory and vocal anatomy and physiology are required in vocal pedagogy; however, singers rely mostly on the sensory and kinesthetic information of the respiratory system to improve and regulate their breath for singing. Imagery is another approach used in vocal training, especially in respiratory training (Boone, 1988).

Singing requires a complete glottal closure necessary to insure high subglottal pressures. Isotonic-isometric vocal function exercises are a series of voice manipulations designed to strengthen and balance the laryngeal musculature. These exercises address laryngeal muscle tonus, onset of vocal fold vibration, and phonation time (Stemple, Lee, Amico, & Pickup, 1994; Verdolini, 1998). They help to achieve complete and symmetrical glottal closure and, therefore, affect the balance of the transglottal air pressure and its resulting airflow. Biofeedback is also used in this aspect of vocal training, mostly auditory feedback. Other exercises use proprioceptive feedback. For example, singers are instructed to position their larynx in a relaxed or lowered posture with minimal tension in the extrinsic laryngeal muscles.

Manipulation of the articulatory and resonance systems is also targeted in vocal training. Singers learn to maximize the size of the vocal tract by lowering the jaw, lifting the soft palate and lowering the larynx. They also become more aware of the articulatory position for phonemes and their durations (Sundberg, 1987).

In summary, throughout vocal training, singers learn to use the respiratory, phonatory and articulatory systems in the most efficient way they can. Analogous to athletes practicing to achieve their maximum output, singers strive to improve strength, endurance, timing and agility (Sabol et al., 1995; Stemple et al., 1994).

Statement of the Research Problem

The singing voice is a topic that has fascinated those researchers trying to determine what makes a singer's voice different from a nonsinger's voice. The review of the literature presented in the next chapter discusses vocal training as the main factor contributing to the vocal differences between these two populations. There are many opinions about the effects of vocal training, but very few are empirical in nature. Contemporary theoretical literature on this topic is quite abundant, but there is a need to refine it using scientific methods and research instrumentation to provide empirical data that indicates that vocal training has an affect on the singing voice, and perhaps on the speaking voice as well.

To this point, much of the research has involved comparisons of singers and nonsingers (e.g., Åkerlund et al, 1992; Brown et al., 1988; Hixon et al., 1973). However, few studies have directly examined the effects of vocal training over a period of time. Specifically, there are few reports on the undergoing changes of the speaking and singing voice over time as a result of vocal training. Historically, a longitudinal study is the best method to evaluate changes that occur over time in a group of subjects (Stevens, 1992; Ventry & Schiavetti, 1986). This method allows the speaking and singing mechanism to be studied as a consequence of vocal training over time.

Rationale for the Study

The data gathered from this study may benefit different professionals involved in the care of the singing voice, such as voice scientists, vocal performers and pedagogues as well as speech-language pathologists. First, the results of this study can be primarily beneficial for voice pedagogues and their students because it may provide information concerning the effects of vocal training and a model of expectations as vocal training progresses.

Second, it may also benefit speech-language pathologists by providing them with a model for modifying the vocal behavior of singers. Also, vocal training techniques may be generalized to the speaking voice and applied to the rehabilitation of vocal pathologies in nonsingers.

Third, this study is relevant to voice scientists, by providing information about the classical singing voice. This voice is characterized as ideal, unique and at the top of the technical hierarchy of singing. For example, operatic singing is one of the most demanding physical activities that one can place on the respiratory, phonatory and articulatory systems, simultaneously (Watson & Hixon, 1985). This study may provide information about how these systems are responding under these stressed or maximal conditions.

Fourth, there are few principles in the production of the singing voice, which are universally accepted and adhered to by the majority of voice professionals (Morrison et al., 1994; Titze, 1994). Some controversial issues involve manipulation of the articulators, i.e. height of larynx, jaw or tongue. This investigation may provide information about the physiological strategies learned by voice major students and the acoustic outcome of these strategies.

Fifth, discrepancies exist between the artistic and scientific approaches used to achieve the most efficient singing voice, specifically the role played by the respiratory system. Because this project involves collecting data from acoustic and respiratory signals simultaneously, a correlation between them is made. This empirical information can be used for didactic training complementing both artistic and scientific approaches.

The following chapter critically reviews contemporary literature regarding the speaking and singing voices of singers and nonsingers. Early studies in the area (e.g. Åkerlund et al., 1992; Brown et at., 1990; 1991) generally concluded that singers as a group, have higher fundamental frequencies, higher sound pressure levels and less perturbation in their voices. As Boone (1982) and Sabol et al. (1995) pointed out, however, these reports are comparisons between singers and nonsingers and do not directly study the effects of vocal training in the human voice. Thus, their conclusions can be misleading. Later studies have tried to correct this error, and they will be reported on in the review that follows. Initial sections discuss acoustic observations of the speaking and singing voice. Later sections review observations of chest wall kinematics and respiratory muscle activity during speaking and singing. The review concludes with a summary and critique of existing literature, followed by a discussion of the specific research questions and hypotheses suggested by the review and examined in this dissertation. The present study serves as a starting point for singing research directed at the analysis of the longitudinal effects of vocal training.

CHAPTER 2
REVIEW OF THE LITERATURE AND RESEARCH QUESTIONS

Acoustic Observations of the Speaking and Singing Voice

Over the past four decades researchers have compared acoustic parameters between the trained voices of singers and the untrained voices of nonsingers. Differences have been found in speaking fundamental frequency (Åkerlund et al., 1992; Brown et al., 1990; Brown, Morris, Hollien, & Howell, 1991), speaking vocal intensity level (Brown et al., 1993), phonational range (Åkerlund et al., 1992; Brown et al, 1993) and jitter ratio (Brown et al., 1990; Murry and Large, 1978). In this review, the speaking and the singing voices of trained and untrained individuals will be examined with regard to the acoustic differences between the two groups.

Speaking Fundamental Frequency

Overall, fundamental frequency (F_0) is the most often studied acoustic parameter in the human voice. It is defined as the rate at which a waveform is repeated per unit time. This oscillatory rate directly reflects the number of cycles per second of vocal folds vibratory motion. Baken (1987) stated

> The vocal fundamental frequency is reflexive of the biomechanical characteristics of the vocal folds as they interact with the subglottal pressure. The biomechanical properties are determined by laryngeal structure and applied muscle forces. Adjustment of the latter is a function of reflexive, affective, and learned voluntary behaviors. (p. 147)

Measurement techniques for determining the speaking fundamental frequency involve obtaining a representative speech sample from reading aloud or speaking tasks. Measurements are in hertz (Hz) or semitones (ST); however a semitone scale is preferable because it reflects exponential growth associated with human perception.

The F_0 of untrained voices has been well defined for over 50 years, and sampled from thousands of subjects ranging in age from the newborn to the elderly. Normative data on untrained Caucasian adults is extensively available (i.e., Hollien & Shipp, 1972; Hollien & Jackson, 1973). For example Baken (1987), stated that

> Fitch and Holbrook (1970) provided good data on speaking fundamental frequency. They evaluated the "middle 55 words of the Rainbow Passage" (Fairbanks, 1960) as read by 100 males (age range of 18 to 25.2 years) and 100 females (age range 17.75 to 23.5 years). The mean SFF for males was 116.65 Hz or 34.0 ST with a standard deviation of 2.11 ST, and for females was 217.00 Hz or 44.8 ST with a standard deviation of 1.70 ST. (pp. 153, 156)

On the other hand, the F_0 of trained voices was less frequently cited and the cited studies incorporated a smaller number of subjects. The SFF (speaking fundamental frequency) of singer and nonsinger groups has been compared during aloud reading of the second paragraph of the Rainbow Passage and during extemporaneous speech. Most of these data show a higher SFF in singers, as a group, than in nonsingers. For example, Brown et al. (1990) compared 19 aged professional female singers (age range of 63-85 years) with 9 aged nonsingers (age range of 75-90 years) and 20 young singers (age range 20-32 years). SFF of aged singers was 195.1 Hz or 43.26 ST with a standard deviation of 3.96 ST. SFF for the aged-matched nonsingers was 175.3 Hz or 41.20 ST with a 2.44 ST standard deviation. For the young nonsingers, SFF was 192.4 or 42.78 ST with a 2.00 ST of standard deviation. When groups were compared, statistically significant differences were found in average SFF of aged nonsingers and standard deviation of SFF of aged singers. In 1991, the above authors mentioned that the

> training received by the professional singer may result in basic and/or age related differences. (p. 311)

Brown et al. (1991) performed a comprehensive study of the SFF involving sixty professional singers and 94 nonsingers. Subjects were divided into three age groups: young (20-35 years), middle-aged (40-55 years) and elderly (65-85 years). Subjects read the second paragraph of the Rainbow Passage. The SFF of these individuals revealed several trends. First, singers exhibited a SFF 1 to 4 ST higher than did nonsingers. These differences were statistically significant for the younger and elderly females and middle-aged men. Second, as a group, sopranos and tenors spoke with a higher SFF than did altos and baritones. Significant differences were found in the middle-age group of both sexes and older females. Third, elderly singers had an overall higher SFF mean than their age-matched group. The authors concluded that singers did not appear to follow the male-female coalescent model of vocal aging proposed by Hollien (1987). This model postulated that: 1) healthy females can expect their SFF to shift to lower levels as they approach old age, and 2) that healthy males can expect their SFF levels to increase as the aging process advances. They reported that singers' noncompliance with the coalescent model may be due to singers' continuous vocal exercise and the meticulous vocal hygiene that they practice throughout their lives. Lastly, singers also had a higher SFF standard deviation than nonsingers, probably due to the greater variation in intonation during reading. The authors hypothesized that

> training in vocal music tends to raise fundamental frequency usage for some singers—the sopranos and tenors especially…these shifts appear reflected in their speaking frequency levels. (p. 314)

Brown et al, (1993) studied the SFF of females during the reading of the second paragraph of the Rainbow Passage and also during a three-second segment of extemporaneous speech. Subjects were 39 singers and 39 nonsingers also divided into three age groups. No significant differences were found between the two phonatory tasks; however, the SFF was higher in the singer group than in the nonsinger group. Statistically significant differences were only found in the elderly nonsinger group, which presented a lower mean SFF (190 Hz). Lastly, singers did not show a drop in SFF with age. The authors hypothesized, again, that

> training in vocal music tends to yield higher SFF levels, particularly in sopranos (p. 223)

Åkerlund et al. (1992) compared the SFF of 10 female singers and 10 female nonsingers under different experimental noise and loudness conditions. Subjects ranged in age from 26-59 years. They read continuous text samples at three different loudness levels as well as under white and filtered noise conditions. The singer group increased their mean SFF significantly more from the normal to the loud conditions than the nonsinger group. In both white and filtered noisy conditions, singers also showed a significant increase in SFF as compared to the non-noisy conditions. They showed an increase of 4.6 and 9.2 ST respectively, while nonsingers only increased 2.4 and 6.8 ST. The authors reasoned that

> female singers raised their mean fundamental frequency more than nonsingers did because they have a wider frequency range, and due to training, can use this without straining their voices. (p. 58)

Therefore, when comparing singers versus nonsingers, differences were found in the mean and standard deviation of SFF reading and speaking tasks. Also, the aging and demanding noise conditions have a different effect on singers' SFF than in nonsingers.

Speaking Vocal Intensity

Vocal intensity is also referred to as the dynamics of the voice (Colton & Casper, 1990). It results from adjustments below the larynx, within the larynx and above the larynx. Titze (1994) reported that

> Below the larynx, changes in intensity are achieved by varying the subglottal air pressure. Within the larynx, changes in intensity are achieved by varying the glottal width. Above the larynx, vocal intensity is obtained by adjusting formants to coincide with harmonics of the source. (p. 218)

Most investigators that study vocal intensity measure the output of voice in terms of sound pressure level (SPL). Units are in decibels (dB), which reflect a logarithmic scale. Measurements of speaking vocal intensity have also been done from reading and speaking tasks. These measurements require a constant mouth-to-microphone distance due to the inverse square law, which states that acoustic intensity is inversely proportional to distance squared from the source (Kent & Read, 1992).

Nonsinger studies revealed that the mean SPL of connected speech in adult speakers during reading tasks is approximately 70 dB (Baken, 1987), while standard deviation during speech and reading is 5.4 dB (Colton & Casper, 1990). Robbins, Fisher, Logemann, Hillenbrand, and Blom, (1981) reported a mean SPL of 69.3 dB (2.94 SD) during the reading of the second sentence of the Rainbow Passage in 15 adult untrained subjects.

Brown et al. (1993) studied the SPL of singers during reading and speaking tasks. Fourteen female singers and 10 nonsingers were divided into two age groups: young (age range of 20-35 years) and middle (age range of 40-55 years). The speaking SPL was analyzed from the reading aloud of the second paragraph of the Rainbow Passage and three seconds of extemporaneous speech. There were no significant differences in SPL between the phonatory tasks. In the young group, the mean vocal intensity of sopranos was significantly different (68.7 dB) than the altos (62.9 dB) and nonsingers (63.3 dB). For the middle-age group, the vocal intensity of nonsingers (62.8 dB) was significantly lower than the vocal intensity of the sopranos (66.7 dB) and altos (65.1 dB). The authors concluded that

> there appears to be a clear trend for the professional singers, especially sopranos, to read and speak at significantly higher vocal intensity levels than nonsingers. (p. 223)

Åkerlund et al. (1992) also studied SPL during continuous text reading. In this study, female singers and nonsingers were compared under three loudness levels and two noise conditions. Singers ranged in age from 26-59 years. Mouth-to-microphone distance was 30 cm. Singers increased SPL significantly more (10 dB) than nonsingers on "loud" and "loudest" conditions. Singers also showed a higher SPL (3dB) in both noise conditions during reading than did nonsingers. However, in the noise conditions there were no significant differences.

Titze and Sundberg (1992) studied vocal intensity in male singers and nonsingers by examining the glottal waveform using inverse filtering of the oral airflow. Subjects consisted of five professional tenors and 25 nonsingers. Singers produced five /pæ/ syllables at five pitch levels and four loudness levels each. Nonsingers produced the same syllable at one pitch level and three loudness levels. Results revealed that singers could achieve 3-4 times greater airflows for the same lung pressures. These resulted in a 10-12 dB difference in SPL between singers and nonsingers. The authors reported that

> singers learn to lower their effective glottal impedance to transfer more power from the source to the vocal tract for a given lung pressure. (p. 35)

In summary, it appears that singers tend to have an overall higher SPL than nonsingers not only during speaking and reading tasks, but also under extreme conditions such as noise. Singers tend to increase SPL by altering subglottal air pressure.

Perturbation Measures

There are at least three perturbation measures; jitter, shimmer and harmonic-to-noise ratio. Jitter and shimmer are referred to as the short-term (cycle-to-cycle) variability in fundamental frequency and intensity, respectively (Horii, 1979,1980). Early investigators, such as Lieberman (1961), studied speech waveforms oscillographically and noticed that no two periods were exactly alike. Sources of perturbations in the voice signal can be found in different stages of the speech production chain: neurologic, biomechanic, aerodynamic and acoustic. However, the most often reported ones are those related to vocal fold irregularities due to variations in mass, tension, muscle or neural activity. Measures indicating increased amounts of perturbation help to detect physiological limits of normal voice production, but also help to detect voice disturbances (Titze, 1994). Perturbation measures correlate well with perceived roughness or hoarseness in voice, so that patients with voice problems would be expected to show a large amount of both frequency and amplitude perturbation (Colton & Casper, 1990). Murry and Large (1978) noticed that the term "roughness" was assigned to a voice with a jitter ratio of 2%. Also, patients with voice disorders or laryngeal pathology had jitter ratios of 8% to 10%.

Concerning the measurement techniques, Colton and Casper (1990) reported that

> Perturbation must be measured from sustained vowel phonations, where a steady pitch level is produced. Connected speech confounds the measure because

> linguistically produced frequency variations can't be separated from frequency variations produced by the biomechanic characteristics of the vocal folds. (p. 188)

Scherer, Vail and Guo (1995) also reported that at least six tokens are required to determine representative voice perturbation values. Frequency perturbation, also called jitter, is obtained by measuring the period of each cycle of vibration, subtracting it from the previous or succeeding period, averaging the differences, and dividing by the average period. This is called jitter ratio (Horii, 1979). If the result is multiplied by 100, jitter can be expressed as a percent change of period relative to the average period (Colton & Casper, 1990).

Nonsingers' jitter were analyzed from sustained /i/ and /u/ vowels produced by three age groups of males and females (Colton & Casper, 1990). Overall mean jitter was less than 0.91 for males with a standard deviation of 0.63. Females' mean jitter was less than 0.7 with a standard deviation of 0.59. These values tended to increase as a function of age.

Murry and Large (1978) hypothesized that since frequency perturbation measures could be predictors of voice disorders, they could also be used in the study of the singing voice as a predictor of a healthy voice. Because singers strive to reduce vocal roughness through training, one would expect that singers would exhibit less frequency perturbation than nonsingers. The above authors compared jitter ratio produced during sustained vowel /ɑ/ by three female singers and five nonsingers (age range was not provided). For modal registers, singers produced a jitter ratio of 0.4 compared with 0.88 for nonsingers. Statistical data analysis was not provided, but the authors concluded that

> singers with training and professional performance experience produced sustained vowels with less cycle-to-cycle variation than subjects with no singing experience. (p. 39)

Murry, Large and Dalgaard (1979) studied jitter values during spoken and sung sustained /ɑ/ vowels. Subjects were four female singers and five male nonsingers, with ages ranging from 26-37 years and 55-71 years respectively. Jitter ratios of the spoken vowel were 0.99 for nonsingers and 0.398 for singers. This last group also produced the sung /ɑ/ vowel in a straight tone with a jitter ratio of 0.668. Jitter ratios of spoken vowels were significantly different between singers and nonsingers ($p = 0.001$).

Brown et al. (1990) compared jitter ratios of elderly female singers (63-85 years) with young female nonsingers (20-32 years) and elderly female nonsingers (75-90 years). All subjects produced sustained phonations of the vowel /ɑ/. No significant differences were found. However, the elderly singers exhibited the lowest mean jitter ratio values (0.22), compared with the young (0.27) and elderly nonsinger groups (0.32). Elderly singers and young nonsingers had a standard deviation of 0.21 and elderly nonsingers 0.38.

Later on, Brown, Rothman, and Sapienza (1997) compared jitter percentages produced by 20 professional singers and 20 nonsingers during spoken and sung vowels. Subjects sustained the spoken and sung /i/ vowels of the word "sea" of "America the Beautiful" (Bates & Ward, 1985). The singer group consisted of 10 males (22-62 years) and 10 females (age ranging 21-61 years). The age-matched nonsinger group consisted of 10 males and 10 females both ranging in age from 22-63 years. Jitter percentages for the spoken /i/ were significantly higher for the male nonsingers than the male singers. The female singers had a higher mean jitter than the nonsingers did, but not significantly. Overall, jitter percentages for the sung /i/ were higher for nonsingers than singers, but this difference was significant only for the females. The authors reported that

> one would expect that during singing, the professional singers would have less jitter in their phonations, but this was not demonstrated, at least statistically. (p. 13)

Sabol et al. (1995) studied the effects of isometric-isotonic vocal exercises practiced regularly for four weeks in 20 voice major graduate students (age range of 21-43 years). Experimental and control subjects sustained the vowel /ɑ, i, u/ at three pitch levels. Pre- and posttest jitter measures were significantly different at comfortable and low pitch levels. At comfortable pitch, the experimental group's mean jitter increased from 0.24 to 0.31, while in the control group the jitter decreased from 0.25 to 0.18. At low pitch, the experimental group's jitter increased from 0.26 to 0.32, while the control group's decreased by 0.01. These findings are surprising, and in contradiction with the previous studies. One would expect that with vocal exercise the irregularities found in vocal fold function due to variation of mass, tension, muscle or neural activity would be reduced.

Shimmer, or cycle-to-cycle amplitude variation, is another perturbation measure. As was the case for the measurement of frequency perturbation, the amplitude of each glottal cycle is measured, subtracted from the previous or following period, and averaged over all differences. This is called the shimmer ratio (Horii, 1980). If the result is multiplied by 100, shimmer can be expressed as a percent change of period relative to the average period (Colton & Casper, 1990).

Nonsingers' shimmer data were taken from sustained /ɑ, i, u/ vowels produced by adults (Baken, 1987). The mean shimmer for males was 0.39 with a standard deviation of 0.31. Females had a mean shimmer of 0.25 with a standard deviation of 0.11. Amplitude perturbation is also affected by vocal pathology. Growths on the vocal folds or poor neural control of the vocal folds would be expected to affect the vibratory amplitude of the vocal folds (Colton & Casper, 1990) .

Comparative studies with singer and nonsinger groups are few. Only one study was found that provided this comparison. Brown et al. (1997) studied shimmer measurements from speaking and singing tasks between male and female singers and nonsinger groups. Each group had 10 subjects with ages ranging between 21 to 63 years. Subjects sustained the spoken and the sung /i/ vowels of the word "sea" from the song "America the Beautiful" for five seconds each. Shimmer values for the spoken /i/ revealed that there were no significant differences between singers and nonsingers. For the sung /i/, nonsingers had significantly higher shimmer values as compared with the singers.

Harmonic-to-noise ratio (H/N) is another perturbation measure and it is expressed in dB or just as a ratio. The voice is a quasiperiodic instrument with two components: quasiperiodic waves and random noise. The H/N is the mean amplitude of the average wave divided by the mean amplitude of the isolated noise components of the waves (Baken, 1987). Colton and Casper (1990) reported that noise may be generated in two ways: 1) there may be a noise source at or near the vocal folds, or 2) greater aperiodicity of vibration may show up as greater noise in the spectrum. In any event, the authors reported that most procedures for the measurement of noise would not be able to distinguish between the two sources.

Scherer et al. (1995) also reported that at least 10 tokens are required to determine representative harmonic-to-noise values. Nonsingers presented a mean H/N of 11.9 dB with a standard deviation of 2.32 dB. No significant difference was found between males and females. The 95% confident limit was 7.4 dB (Baken, 1987).

Comparative studies of H/N with the singing population, as for shimmer, are rare. Brown et al. (1997) compared the same singer and nonsinger subjects during the sustained spoken and sung /i/ vowels for H/N. The authors reported no significant differences between singers and nonsingers for the speaking sample. For the sung /i/sample, male singers showed a significant larger H/N than the nonsinger group. No differences were found in the female group.

In summary, singers, as a group, appear to have lower perturbations values than in nonsingers for both the speaking and the singing voice. This is especially evident in the means of jitter and shimmer.

Phonational Frequency Range

Measures of SFF provide information about how a speaker uses his voice. The phonational frequency range (PFR) provides information about basic vocal ability and reflects the physical limits of the phonatory mechanism (Baken, 1987). Hollien, Dew and Philips (1971) defined PFR as

> the range of vocal frequencies encompassing both the modal and falsetto registers; its extent is from the lowest tone sustainable in the modal register to the highest in falsetto inclusive. (p. 755)

The phonational frequency range, as opposed to the singing range defined by Britto and Doyle (1990) and Brown et al. (1993), includes modal and falsetto registers due to the difficulty of perceptually differentiating them. Pulse or fry register is excluded because it is not normally used, continuously, for running speech.

Measurement techniques use a pitch-matching procedure. The subject is asked to sustain one of the following vowels /ɑ, æ/, at the same pitch as the stimulus tone presented by an oscillograph, automatic tuner or a keyboard. Beginning at a comfortable fundamental frequency the stimulus is lowered in 1 or 2 ST steps to the subject's lowest tone in the modal register. The stimulus frequency then ascends from the comfortable level until falsetto register is unsustainable (Baken, 1987; Colton & Casper, 1990). This procedure is done three times each. The lowest and the highest sustained tones are at the low and high end of the subject's PFR, respectively. PFR is expressed in either Hz or semitones. Kent, Kent and Rosenbek (1987) reported that intra- and intersubject variability on PFR is large and may be affected by practice, motivation or instructions.

Nonsinger's data revealed that young adults should be able to produce a PFR of three octaves (Hollien et al., 1971). Colton and Casper (1990) reported that a young male group (17-26 years) had a PFR of 39.06 ST, a middle-aged male group (26-65 years) had a PFR of 28.77 ST, and an elderly male group (68- 89 years) had 26.55 ST. The PFR of young females (18-38 years) was 36.03 ST, of middle-aged (35-70 years) was 30.75 ST, and an elderly female group (66-93 years) had a PFR of 25.06 ST. Even though PFR was found to decrease with age in both males and females, age apparently had no significant affect on this acoustic measure (Hollien et al., 1971; Baken, 1987).

The results from comparative studies with singers usually have agreed that singers have a wider PFR; however, discrepancies exist as to how wide the range is. Sundberg (1977) reported that singers need to develop full control over the pitch range of two octaves or more. Colton and Casper (1990) reported that young adults should have a PFR of three octaves, with singers slightly higher than nonsingers.

Brown et al. (1993) compared PFR produced by professional female singers and nonsingers. Seventy women were divided into three age groups: young (20-35 years), middle-aged (40-55 years) and elderly (65-85 years). Overall, singers had a wider PFR occurring mostly at the high end than did nonsingers. The young group showed a mean PFR of 45 ST for sopranos, 44 ST for altos and 38 ST for nonsingers. The middle-aged group had a mean PFR of 40 ST for sopranos, 44 ST for altos and 39 ST for nonsingers. The elderly group presented a mean PFR of 38 ST for sopranos, 35 ST for altos and 31 ST for nonsingers. Even though nonsingers always had a lower PFR mean, this trend was not significant. The authors were surprised by the lack of statistical significance and reported

> it would seem that professional singers would exhibit much larger PFR due to their mastery of voice. (p. 223)

Åkerlund et al. (1992) also compared PFR produced by 10 female singers with 10 female nonsingers. Subjects ranged in age from 26-59 years. Trained singers had a significantly wider PFR than the nonsingers did: 38.4 ST and 29.1 ST, respectively. The highest fundamental frequencies for the singers were much higher compared with nonsingers.

Sabol et al. (1995) studied the effects of four weeks of isometric-isotonic vocal function exercises on PFR. Twenty voice major graduate students with ages ranging from 21 to 43 years were divided into experimental and control groups. There were no significant differences between the pre- and posttest data, or between the control and experimental group. The authors suggested that

> improved measures of vocal function do not necessarily affect frequency range of the singer who may already have developed a maximum frequency range with the repertoire and singing exercises. (p. 34)

In conclusion, the above studies showed that, overall, singers have a wider PFR than nonsingers, especially at the higher end of the PFR. This trend is statistically significant.

Speech Temporal Measures

Speech spectral measurements provide information about the resulting vocal output and reflects the coordination of the respiratory, phonatory and articulatory systems. On the other hand, speech temporal measurements reflect the interaction and the neuromotor coordination of the phonatory and articulatory systems. Durational measures of speech can encompass sentences, words, diphthongs, vowels, consonants or even smaller segments.

The studies cited below provide normative data acquired from nonsingers and singers and compare the two the groups. Sentence duration is one of the speech segment measurements that has been analyzed in comparative studies. Shipp, Qi, Huntley and Hollien (1992) measured the third sentence of the "Rainbow Passage" in three age groups of normal male talkers. Subjects were divided into three age groups: young (21-35 years), middle (46-71 years) and aged (77-90 years). The young group presented a mean sentence duration of 6.67 sec. with a standard deviation of 0.51. The middle-age group had a mean of 7.99 sec. with a standard deviation of 0.85. The aged group had a mean of 10.80 sec. with a standard deviation of 2.35. Although older subjects took longer to produce the sentence, this difference was not statistically significant.

Brown et al. (1997) compared sentence duration of 20 singers and 20 nonsingers. The singers consisted of 10 males and 10 females with ages ranging from 21 to 62 years. The nonsingers were 10 males and 10 females with ages ranging between 22 to 63 years. Subjects read the "Rainbow Passage" and the second sentence was measured. Singers demonstrated a slightly longer duration than did the nonsingers. The male and female singers' sentence duration was 3.8 and 4.0 seconds, respectively. Male and female nonsingers' sentence duration was 3.3 and 3.7 sec., respectively. However these differences were not significant.

Diphthong duration was also compared in the above study. Temporal measures of the "whi" of the word "white" were compared between singers and nonsingers. No trends or significant differences were observed between these two groups and their sex.

Consonant duration measurements are more complex because consonants differ significantly among themselves and with their coarticulatory environment. Voiceless stop consonants are unique among the speech sounds. There are many temporal measurements of stop consonants, e.g., measurements of voice onset time (VOT), release burst, formant transition, etc. The essential articulatory feature of a stop consonant is a momentary blockage of the vocal tract and airflow (Kent & Read, 1992). This blockage called closure duration is represented by a stop gap in the acoustic signal. As Baken (1987) stated

> during this interval air pressure rises behind the point of closure to be released as a burst of acoustic energy. (p. 369)

Measurement techniques of this closure duration involve the use of the acoustic signal or the subglottal air pressure. In the first case, the closure duration corresponds to the acoustic interval seen in a waveform or a spectrogram. The primary criteria for identification of the closure are 1) a region of reduced energy, and 2) other evidence of articulation preceding or following the closure. The utilization of the subglottal air pressure pulse for measuring the closure duration is more precise and versatile than the acoustic signal because it can easily identify phoneme boundaries. However, the measurement procedure of subglottal pressure requires a more technical approach than spectrography (Brown, 1987).

Nonsinger's data of the closure duration in voiceless consonants was measured using the acoustic signal. It was found to be typically between 50-150 ms (Kent & Read, 1992).

Comparative studies between singers and nonsingers were performed by Rothman, Brown, Sapienza and Morris (1998). Twenty singers and 20 nonsingers read the "Rainbow Passage." The acoustic signal was used to measure the closure duration of the stop consonant /t/ of the word "white". The mean duration of the closure duration was 51.5 ms for singers and 42 ms for nonsingers. These differences were not statistically significant.

Brown (1977) and McGlone (1977) measured intraoral air pressure, consonant and vowel durations in singers and nonsingers during speaking and singing tasks. The above authors concluded that

> whereas nonsingers do not appear to differentiate speech gestures for singing compared to speaking, singers do. This may be directly related to their specialized vocal training. (p. 3)

In summary, temporal measures of sentences, diphthongs and closure duration of consonants tend to be longer in singers than in nonsingers. This trend is more pronounced in speaking than in singing tasks.

Vocal Vibrato

Vibrato is a rhythmic oscillation of the fundamental frequency mostly characteristic of the singing voice. Seashore (1967) described vibrato as a

> pulsation of pitch, usually, accompanied with synchronous pulsations of loudness and timbre, of such extent and rate as to give a pleasing flexibility, tenderness and richness to the tone. (p. 33)

Measurement techniques use sustained sung vowels, generally /i/ or /ɑ/. Acoustic parameters of vocal vibrato include frequency vibrato in pulses per second, frequency variation of the vibrato pulse above and below the mean in percentage, amplitude vibrato in dB and amplitude variation above and below the mean in percentage.

Much controversy exists about vibrato production and perception. Vibrato related-changes have been reported in laryngeal, respiratory, and supralaryngeal muscles as well as in subglottal pressure, transglottal aiflow and glottal area. There have been at least five attempts to explain the physiological mechanism underlying the vibrato production.

Appelman and Smith (1985) studied abdominal muscle function during vibrato productions using cineoflurographic and surface EMG signals. They concluded that vibrato results from the subglottal air pressure's rhythmic pulses due to abdominal muscle contractions that are under the singer's control. These pulses have an effect on the amplitude and frequency modulation of vibrato.

Shipp, Doherty, and Haglund (1990) used hooked wire electromyographic signals (EMG) on the cricothyroid muscle (CT) during vibrato. CT activity not only modulated the frequency of the vibrato but also preceded it. Shipp et al. hypothesized that vibrato frequency can have two types of production: one caused by the voluntary contraction of the abdominal muscles which affects subglottal air pressure, and the other, caused by the involuntary contraction of the CT muscle.

Ladefoged (1974) reported an entirely different physiological mechanism from that of the cricothyroid-based mechanism. He suggested that frequency vibrato production involves some adjustments of the position of the arytenoid cartilages in space and tension.

Horii (1989) reported that a resonance-harmonic hypothesis alone could sufficiently explain the various phase relationships of amplitude vibrato. The resonance-harmonic hypothesis states that the amplitude vibrato is the result of resonance-harmonic interaction rather than an active amplitude oscillation.

Finally, Sapir and Larson (1993) correlated sustained vibrato productions of /ɑ, i, u/ vowels with the frequency of EMG signals. Surface electrodes were placed on the anterior suprahyoid region, extralaryngeal muscles, massetter and upper perioral muscles. They reported that vibrato is a consequence of anterior suprahyoid muscles, which change the vertical and horizontal stiffness of the vocal folds.

The controversy about vibrato not only involves its production but also its perception. Rothman (1987) and Rothman and Timberlake (1984) reported that there is no unanimity in the perceptual categorization of vibrato when compared with other vocal oscillatory behaviors like wobble or tremolo. However, despite the variance of listeners' judgments, there are acoustic parameters that can help to differentiate between vibrato samples judged as good or bad. These parameters are frequency vibrato in pulses per second (pps), frequency variation above and below the mean in percentage and amplitude variation in dB.

Frequency vibrato is usually found between 4.5 to 6.5 pulses per second (Rothman, 1987; Sapir & Larson, 1993; Titze, 1994). The frequency of the vibrato pulse above and below the mean can vary from 0 to ± 3 % (Titze, 1994) or from one-half to more than two semitones (Horii, 1989). This last acoustic measure can be influenced by the pitch and loudness at which the vibrato is produced. The amplitude vibrato has a range of 2-3 dB to 8-10 dB (Rothman, 1987; Sapir & Larson, 1993).

Sundberg (1987) reported that

> Almost all professional opera singers develop vibrato without thinking about it and without trying actively to acquire it. Vibrato develops more or less by itself as voice training proceeds successfully. (p. 163)

Singer's Formant

In 1934, Bartholomew reported that operatic singers have an extra formant. About 40 years later, Sundberg (1974, 1977) offered a physiological explanation for it. First, Sundberg analyzed the singing voice of tenor Jüssi Bjoerling (1911-1960) and found that the spectrum of his voice had a major resonance around 3000 Hz, particularly in the presence of a loud orchestral accompaniment. Spectrographic analysis revealed that an orchestra's output and speech production have their energy peaks around 500 Hz. However, for the operatic singer, the peak of acoustic energy is around 2-3 kHz. Secondly, Sundberg (1974) modeled this peak of energy with small resonator inside the vocal tract in the epilaryngeal region. The exact frequency was determined by the effective acoustic length of the small resonator, which typically is 2.5-3.0 cm. He concluded that this extra formant is the direct result of lowering the larynx and the expansion of the bottom of the pharynx. Hollien and Keister (1978) related this formant to nasal resonance, but later on, in 1983, they reported to have no evidence to support this hypothesis.

More recent studies reported that the singer's formant is a strong area of energy centered around 3000 Hz. This formant is generally found between the third and fourth regular formants, encompassing a resonance region from 2800-3500 Hz (Titze, 1994; Weiss & Morris, 1996).

There is a practical reason for the singer's formant. In a symphony orchestra, the highest level of SPL is found around 500 Hz. It is around this frequency that speech also has its maximum SPL. This means that a normal speaker would not be audible while the orchestra is playing. However, a singer is audible due to the singer's formant. Its frequency is located where the orchestra's sound is rather weak.

The singer's formant has been observed primarily in professional male singers of Western opera and concert performers (Sundberg, 1974). This formant is clearly present in trained tenors and bass-baritones, more sporadic in trained mezzos, and hardly distinguishable from other harmonic clusters in trained sopranos (Weiss & Morris, 1996). Soprano singers do not seem to have singer's formant. Sundberg (1987) showed that instead of the singer's formant, female singers tend to widen their jaw openings with increasing fundamental frequency (F_0) in such a way that the first formant (F_1) is tuned to the area of the F_0. This causes a SPL gain of up to 30 dB when the F_0 is higher than the normal value of the F_1.

Another factor influencing the level of the singer's formant is the vowel. Sundberg (1987) reported that

> for male professional singer's vowels with a high second formant (F_2), such as /i/ and /e/, the singer's formant is, on the average about 12 dB weaker than the

> overall SPL. For the vowels with a low F_2, such as /u/ or /o/, the corresponding average is about 20 dB. (p. 119)

The singer's formant adds clarity, projection and timber differentiation to the voice (Sataloff, 1992; Sundberg, 1977). However, little is known about how singers develop this skill. Weiss & Morris (1996) reported that

> the presence of the singer's formant seems to be largely a factor of voice training. (p. 54)

In summary, the literature review of acoustic observations of the singers and nonsingers voice revealed that there are several spectral and temporal differences in the speaking and singing voice of these two populations. Singers present a high mean and standard deviation of the speaking fundamental frequency and SPL. Sopranos and altos have the highest values. Singers' voices present lower perturbation measures in both speaking and singing tasks, especially for frequency perturbation or jitter. Singers also have a wider phonational frequency range, especially at the higher end. And finally, vibrato and the singer's formant seems to be exclusive vocal characteristics of the singer's voice.

The focus of this project was to examine the final output of four semesters of vocal training in 14 voice major students. There were 10 dependent variables taken from two speaking tasks and 11 dependent variables taken from two singing tasks. However, it should be recognized that in order for an acoustic product to be considered within the normal limits or aesthetically pleasing, other subsystems must be involved: primarily the respiratory system. The respiratory system is the principal power system for the development of subglottal pressure needed for initiation and maintenance of vocal fold vibration. The following section is a review of the role of the respiratory system in the production of speech and singing. Part of this project will describe data from 4 subjects who participated in initial work that examined the contribution of multiple subsystems used during speech and singing. For these four subjects respiratory kinematics and electromyography (EMG) were used to examine the respiratory system's role during speaking and singing as a function of three semesters of vocal training.

Chest Wall Kinematic Observations

The respiratory system's main function is metabolic in nature. Its primary purpose is to provide oxygen to the cells of the body and to remove carbon dioxide from them. Its secondary function occurs during voice production. The respiratory system is the power source of the vocal mechanism because, in concert with the laryngeal system, it generates subglottal pressures necessary for vocal fold vibration. Voice practitioners call the combination of thoracic and abdominal muscle contraction the "support" of their voices (Sataloff, 1988). It supplies the driving pressures necessary to initiate and maintain vocal fold vibration as well as to control linguistic parameters of intensity and stress (Weismer, 1985). Anatomically, the respiratory system's main components used for ventilation, speech breathing and singing are the lungs, rib cage, diaphragm, and abdomen. All parts, other than the lungs are considered to make up the chest wall (Hixon, 1991).

Respiratory kinematics is one technique used to study the motions of the chest wall (Konno & Mead, 1967). Displacement of lung volume is achieved through the combined movements of the chest wall as the displacements of the rib cage and abdomen are linearly related to lung volume displacement. This technique provides an estimation of the rib cage and abdominal volumes from measurements of the displacements of their respective surfaces. When the upper airway or larynx is closed, any change in the volume of one part of the chest wall is equal and opposite of the other part. The closed airway permits a constant volume to be displaced between the rib cage and abdomen. This maneuver is typically completed during a calibration procedure referred to as an isovolume maneuver. By calibrating the displacement of the rib cage and abdomen to be equal but opposite during the isovolume maneuver (slope = -1), the displacement of volume can be directly related to the measurement of the anteroposterior dimension change of both parts (Konno & Mead, 1967). Other calibration maneuvers include measurement of the maximum rib cage and abdominal capacities; the objective is to achieve normalization of respiratory data as a function of individual subject size (Hoit & Hixon, 1987). Lastly, a relaxation maneuver serves as a reference point, where at a given lung volume the rib cage and abdominal muscles are relaxed against a closed airway. Inferences can be made regarding the muscular pressures developed during breathing, speaking, or singing tasks. The relaxation characteristic represents a balanced muscle force. Therefore, data points lying outside the relaxation characteristic indicated either a positive expiratory or negative inspiratory force (Hixon, 1991).

Different non-invasive methods have been used to study speech breathing, specifically chest-wall displacement and aerodynamic measures. Magnetometers had an advantage over other methods in the study of singers' respiratory kinematic behavior (Bless, Hunker, & Weismer, 1981). Singers are expected to have distinct rates of inspiration and expiration as well as other aberrations in timing and control. The linearized magnetometer system provided a uniform output in a variety of anteroposterior dimensions of the chest wall in different subject sizes, and was less susceptible to slippage, distortion, and artifact of movement (Baken, 1987; Bless et al., 1981).

The linearized magnetometers consist of two pairs of sensing coils. Each pair includes a generator coil which produces an alternating electromagnetic field and a sensor coil which measures a voltage that is inversely proportional to the cube of the distance between the coil pair (Baken, 1987). The generator coils are attached to the front of the torso at the level of the manubrium (rib cage) and umbilicus (abdomen). The sensor coils of each pair are attached to the back of the torso in locations that are at the same axial level to the anterior generator coil placements. A calibration routine is needed to assure accurate conversion of chest wall displacement to voltage and will be discussed in the Methodology chapter.

Respiratory Function in Nonsingers

The following are observations of respiratory function during both ventilation and breathing for speech produced by nonsingers with normal vocal quality:

1. The combined rib cage and abdominal wall displacements reflect total lung volume change;
2. The rib cage expands as lung volume increases during inspiration and compresses as lung volume decreases during expiration;
3. The abdomen displaces outward on inspiration and inward on expiration;
4. The volume of air used during tidal volume breathing is approximately 0.5 liters;

5. The lung volume used in conversational speech does not encompass a large proportion of the vital capacity (VC); generally, conversational speech falls within a range of 60% to 35% of VC;
6. The combined actions of the rib cage and abdomen produce a respective expansion and contraction per given lung volume. This action produces the "initial phonation threshold pressure" needed to initiate voice production once the vocal folds are closed, i.e. the required subglottal pressure to maintain normal voicing and loudness;
7. The initiation of speech production is at lung volume at or slightly below the end inspiratory cycle of tidal volume breathing (40%);
8. The termination of speech is at lung volumes slightly above or below the resting expiratory level (REL) at approximately 35% of the vital capacity; and,
9. An individual speaker is highly consistent with respect to how the chest wall interacts with changes lung volume during comfortable effort speech.

The phonatory subglottal pressures are relatively low, 3 cm H_2O in very soft phonations and up to 20 cm H_2O for loud phonations. For speech production purposes, only 5-7 cm H_2O is needed (Minifie, Hixon & Williams, 1973). In order to maintain a constant subglottal air pressure, active muscular forces supplement passive recoil forces of thoracic and abdominal cavities. As the recoil forces change with the lung volume, different degrees of muscular forces are continuously needed to generate such constant pressures during phonation.

Respiratory Function in Singers

Singers place high demands on the respiratory system. They need to generate high frequencies and amplitudes as well as prolonged phonations. In exceptional cases, singers use pressures as high as 70 cm H_2O (Leanderson & Sundberg, 1988).

Watson and Hixon (1985) studied respiratory kinematics in classically trained singers by observing chest and abdominal wall movements during speaking and singing. There were no differences between these subjects and nonsinger subjects in speaking tasks, however differences were observed in singing tasks. The following are observations of the respiratory function during classical singing:

1. Even though most of the lung volume excursions ranged from 60-30% of VC, subjects encompassed a lung volume ranging from 100-15% of VC (while speech tasks encompassed 60-35%). This results in the recruitment of accessory inspiratory muscles not only to achieve 100% of VC, but also to counteract the expiratory recoil forces. Extensive use of expiratory muscles was also needed to achieve 15% of VC;
2. Breath groups started at 90-60% of VC (for speech started at 60%) and terminated at 30-15% of VC (for speech terminated at 35%);
3. Singers exhibited continuous adjustments of the rib cage, abdomen and lung volume throughout the singing task;
4. The chest wall was frequently distorted and the abdomen was in a less expanded position compared with relaxation;
5. The rib cage had a larger contribution than the abdomen, not only in inspiration but also in expiration;

6. During expiration, the rib cage was largely expanded, generating higher negative air pressures for continuous airflow;
7. Singers recruited higher muscular pressures because of higher subglottal pressure demands (50 cm H_20 or more); and
8. Abdominal muscles contracted throughout functional residual capacity (FRC). This facilitated fast diaphragmatic contractions for rapid inspirations.

In summary, singers produce higher fundamental frequencies and louder phonations for longer periods of time than nonsingers. In order to achieve these demanding productions without damaging the phonatory system higher subglottal pressures are generated by breathing up to 100% of the vital capacity. Subglottal pressure demands can go up to 70 cm H_2O. Because many of these air pressure requirements are above the ones that the relaxation pressure can provide, muscle force needs to be generated. Principal and accessory muscles of inspiration and expiration are recruited.

Electromyographic Observations

The respiratory system is driven by muscular and nonmuscular forces. The vocal demands of singers are achieved by using high subglottal air pressures, which are above those that the relaxation pressure can provide. This means that the singer needs to recruit muscular forces to manipulate lung volume and to obtain higher subglottal air pressure.

Linearized magnetometers can provide information about the overall contribution of the rib cage and abdomen related to lung volume. Electromyography (EMG) on the other hand provides information about the function of a specific muscle or muscle groups in the respiratory process during speaking and singing.

EMG measures muscle action potentials produced during movement. Muscle action potentials are recorded by electrodes, placed in or near a muscle, which pick up the electrical potentials associated with muscular contraction (Basmajian & De Luca, 1985).

Surface electrodes record integrated action potentials caused by electrical disturbances in a large muscle mass. The surface EMG technique has been severely criticized and needs to be interpreted cautiously due to contaminations of signals from neighborhing muscles and movement artifacts (Eblen, 1963; Sapir & Larson, 1993). However, EMG studies have been extremely useful in understanding the relationship between the acoustic signal, respiratory muscle activity, subglottal air pressure and lung volume changes during speech (Draper, Ladefoged & Whitteridge, 1959). Moreover, recent studies have shown that EMG is a valid and reliable method (Watson et al., 1989). Weismer (1985) further reported that

> EMG studies accompanied by the kinematic technique can provide a much more fine-grained understanding of breath for speaking and singing purposes than is currently available. (p. 65)

Watson et al. (1989) used surface EMG to study the electrical activity of abdominal muscles involved in the singing process. They compared singing versus speaking tasks in trained classical singers. During singing, external and internal obliques as well as transverse abdominis had an increase in amplitude of 35μV. These findings support the concept that the abdomen plays an important role in posturing of the chest wall for singing, while the rib cage has a major role of pressurization of the pulmonary system.

Leanderson, Sundberg, and Euler (1987) used EMG to study the relationship between subglottal air pressure and abdominal activity. Results showed an active role of the external oblique muscle in the generation of pressure variations during singing.

The biomechanical function of the singing process has also received little attention. The majority of the literature on EMG during respiratory function in singers has studied the contribution of the abdominal muscles during phonation. Muscle activity contributes not only to posturing the chest and abdominal walls but also to the fast and dynamic control of the subglottal pressure that is required for voice production. In order to achieve high subglottal pressures, accessory muscles of inspiration are required. It seems that there is a lack of knowledge in this area, specifically concerning the accessory muscles of inspiration. If we view the singer as an athlete who needs exercise for strength, endurance, timing and agility, than understanding the training that the singers go through is critical for the understanding of the mechanism of the respiratory system in the singing voice, not only its expiratory, but also its inspiratory role.

Statement of the Purpose

The majority of the above studies compared voices of singers and nonsingers and found acoustic or physiological differences between these two groups. Most of these studies reported that the differences are due to extensive vocal training as well as vocal hygiene practiced throughout the singers' life. There is a great need to directly evaluate the effects of vocal training.

This investigation evaluated the respiratory, phonatory and articulatory function during vocal training by simultaneously recording the respiratory kinematic and EMG muscle activity of one accessory inspiratory and two expiratory muscles, as well as the acoustic signal produced during speaking and singing. The general goal of this project was to describe the differences of the respiratory, phonatory and articulatory system when subject to a period of vocal training. Specific interest is in describing how the upper vocal tract functions during the four semesters of vocal training and to compare that function with baseline measures taken during the first semester. Vocal training, as it was described in the previous chapter, involves the following: 1) breathing exercises with particular emphasis in strengthening the abdominal muscles, 2) isometric-isotonic vocal function exercises, and 3) articulatory precision exercises. The results of this investigation will provide a description of the effects of vocal training on the acoustic output involved in the singing production. Finally, a descriptive report on a small subset of subjects who completed the study on the kinematic and electromyographic contributions during speaking and singing will be included.

Research Questions

The primary purpose of this study was to investigate the acoustic and temporal effects of four semesters of vocal training on voice major students. A secondary purpose was to identify the changes that occur in the respiratory system and muscle force generation after three semesters of vocal training. Specific questions addressed in this study included the following:

1. Is there a difference in the functioning of the laryngeal system in voice majors after four semesters of vocal training that can be detected in the acoustic signal?

2. Is there a difference in the functioning of the articulatory system in voice majors after four semesters of vocal training that can be detected in temporal measures?
3. Is there a difference in the rib cage and abdominal movements in voice majors after three semesters of vocal training that can be detected in respiratory kinematic signals?
4. Is there a difference in the muscle force generation of the pectoralis major, rectus abdominis and external oblique muscles in voice majors after three semesters of vocal training that can be detected in EMG signals?

Hypotheses Regarding the Effects of Vocal Training

This study examined the changes on the acoustic, chest wall and surface EMG signals taken during speaking and singing tasks. These signals provided information about the function of the respiratory, laryngeal and articulatory systems when subjected to an extended period of vocal training. The nature of this experimental design required a longitudinal research study. Acoustic data were collected once a semester for four consecutive semesters. Physiological data were collected for three semesters. Baseline measures were taken on the first semester. The population in which these relationships were examined consisted of a volunteer sampling of voice major students enrolled in vocal training

The following are hypotheses regarding the effects of vocal training:

1. The acoustic characteristics of the speaking voice within voice major students will change after four consecutive semesters of vocal training;

2. The acoustic characteristics of the singing voice within voice major students will change after four consecutive semesters of vocal training;
3. The respiratory excursions of the rib cage and abdomen wall within voice major students will change after three semesters of vocal training; and
4. The muscle force generation of the pectoralis major, rectus abdominis and external oblique muscle within voice major students will change after three semesters of vocal training.

CHAPTER 3
METHODOLOGY

Research Design

The design of this project was a longitudinal research design, which examined the effects of vocal training on the respiratory, phonatory and articulatory systems of voice major students. Primary report of this investigation focuses on the outcome of vocal training on the acoustic characteristics of speaking and singing function. Baseline measurements were obtained during the first semester of enrollment in vocal training. Each subject participated in one experimental session per semester during at least three consecutive semesters. Most subjects were recorded for four semesters, however three subjects were recorded only during three semesters. Therefore, this longitudinal study was a case of within-subject design with incomplete repeated measurements (Marks, 1994; Ventry & Schiavetti, 1987).

The secondary portion of this report focuses on physiological characteristics of the respiratory system, measured from chest wall kinematics and surface EMG signals. These physiological data were collected in a smaller subset group of subjects. In order to study the relationship between acoustic and physiological data a correlation design was used (Cone & Foster, 1998).

Dependent variables were classified as nominal, ordinal and continuous. Potential measurement errors include the following: 1) lack of stability in the continuous response variables; 2) lack of consistency by the technician collecting and analyzing the data; and 3) error in the measuring instrument. To minimize the lack of stability in the continuous response variables, warm up vocal sessions were held with the singers. Before each recording session, subjects performed pitch and loudness range tasks in a glissando manner and read a modified "Rainbow Passage." To address the lack of consistency in the technician's data collection procedure, the same researcher administered each experimental session to provide consistency of instruction and procedure. Intra-measurer agreements were made from data collection forms to estimate the reliability of the measurements. To minimize error in measuring instrument, calibration procedures were performed at the end of each experimental session. Lastly, intraclass correlation coefficients were calculated to observe measurement errors in response variables.

A volunteer sampling was used since subjects were chosen from those available in the University of Florida Music Department who agreed to participate and sign the *Informed Consent Form* (Appendix A). Subjects were recruited by verbal advertisement in the Voice Studio classes. Any selection, geographical or Berkson's (Marks, 1994) bias can be identified by the *Vocal Health and Background Questionnaire* (Appendix B). Subjects were asked to complete this questionnaire before being recorded.

Sample Size Determination

Sample size determination was based on a hypothesis testing. The appropriate null hypothesis stated that no differences were found in speaking or singing voices of the voice major students after a three or four semester period of vocal training, i.e.,

H_0: $\mu1=\mu2=\mu3=\mu4$ or H0: $\mu d=0$

The alternative hypothesis or the one that the researcher wanted to prove, stated that three or four semesters of vocal training had an effect on the speaking and singing voices of voice major students, i.e.,

H_0: $\mu1\neq\mu2\neq\mu3\neq\mu4$ or H0: $\mu d\neq0$.

where $\mu1$, $\mu2$, $\mu3$ and $\mu4$ were defined as the true mean of all numerical response variables for each of the four semesters respectively. μd was defined as the true mean difference of all numerical response variable changes among the four semesters. A two-tailed analysis was used to evaluate the direction of the difference.

Calculation of the sample size requires only one response variable (Marks, 1994). In this investigation, vibrato pulse rate was the variable used to determine the sample size, because vibrato is one of the vocal characteristics that are developed or enhanced during vocal training (Sundberg, 1987). This rhythmic oscillation has a frequency mean range between 4.5- 6.5 pps (Rothman, 1987; Sapir & Larson, 1993; Titze, 1994). The common standard deviation, denoted σ, can be estimated from this range:

$6.5 - 4.5 = 2$ pps, and $\sigma \approx$ range /4, so $\sigma = 0.5$ pps

Because this research project involved a repeated measures design, the standard deviation of the different scores between the first and the second semesters was needed.

Therefore, the average standard deviation of the different scores, denoted as the σd was calculated assuming that this difference is equal in both semesters (Marks, 1994):

$$\sigma d = \sqrt{2 \times \sigma^2} \Leftrightarrow \sigma d = \sqrt{2 \times (0.5)^2} \Leftrightarrow \sigma d = \sqrt{2 \times 0.25} \Leftrightarrow \sigma d = 0.5$$

The critical relevance difference of the vibrato measured in pps between at least two semesters was also estimated. This difference is also called bound (B), and was decided to be 2 pps. That is, an increase of 2 pps in vibrato frequency from the first to the second semester was considered a critical enhancement of the subject's voice. σd and B were combined to compute Delta, defined as

$$\text{Delta} = B \div \sigma d \Leftrightarrow \text{Delta} = 2 \div 0.5 \Leftrightarrow \text{Delta} = 1$$

The significance level (α), or probability of committing a type I error, was predetermined at 0.05. The power of a statistic test ($1\text{-}\beta$), or ability of the test to reject the H_0, if H_0 was false, was set at 80%. *Table of Sample Size Required to Test* H_0: $\mu 1 = \mu 2$ *for Various* α *and Power* (Appendix C) was used to estimate the sample size. Row 110 indicated that 8 subjects were required with a Delta of 1, an α of 0.05 for a two-tailed analysis and a power of 80%.

Therefore, at least eight subjects were needed in order to detect an average difference of 2 pps in the mean vibrato frequency range between two semesters of vocal training if that difference truly exists. A balanced female/male sample was not taken in consideration in this design because subjects are being compared within their baseline measures taken during the first semester of vocal training. However, due to subject drop out rate in a repeated measures design study (Marks, 1994; Ventry & Schiavetti, 1986) as well as higher standard deviations in other variables, the investigator recruited as many subjects as possible.

Subjects

Fourteen subjects participated in this investigation: 12 females (mean age = 18 years) and 2 males (mean age = 20 years). They were recruited from an available population of undergraduate voice students enrolled in Voice Studio classes at the University of Florida's Music Department. Inclusion criteria for subject selection included the following: 1) ages between 17-25 years; 2) native American-English speakers with normal articulation, voice, resonance, language and hearing abilities as judged by a certified and licensed speech-language pathologist; 3) no history of respiratory or voice disorders; and 4) symptom-free of allergies or colds on the days of testing. Exclusion criteria for participants were 1) smokers and 2) professional singing experience. The selected subjects' physical characteristics are noted in Table 3-1.

Prior to the experimental session, every subject received a written and verbal explanation of the procedures used in the investigation. All signed the *Informed Consent Form* (Appendix A) approved by the Institutional Review Board at the University of Florida.

Demographic data were collected for each subject by filling out the *Vocal Health and Background Questionnaire* (Appendix B). This included information about subjects' social, family and medical history, voice usage, intensity and frequency of vocal training, voice classification and extracurricular singing activities. This information can be found in Table 3-2. Prior to enrolling in voice studio classes at the University of Florida, all subjects exhibited singing experience from 1 to 7 years, with a mean of 3 years. They had participated in school and/or church choirs or had private lessons.

Table 3-1. Selected physical characteristics of the subjects.

Subject (ID)	Sex	Age (yr.)	Height (cm)	Weight (Kg)	Vital Capacity (L)
AW	F	18	165.10	52.27	3.80
BM	F	19	170.18	60.45	2.90
CW	F	18	170.18	109.09	*
JD	F	18	149.86	47.73	2.70
JH	F	19	157.48	86.36	*
LB	F	19	157.48	51.82	2.40
MM	F	20	165.10	68.18	3.60
MN	F	19	162.56	61.36	2.80
RC	F	19	160.02	50.00	3.70
RH	F	18	165.10	72.73	4.10
SL	F	17	170.18	52.27	3.65
SG	F	18	162.56	52.27	3.20
CH	M	20	174.63	68.18	5.10
JP	M	20	171.45	73.64	5.00

* Due to subject's physical characteristics, physiological signals were not collected. Only acoustic signals were recorded.

Phonatory Tasks

Subjects performed speaking and singing tasks. Speaking tasks consisted of the production of a sustained vowel and the reading of a paragraph aloud. Subjects sustained the vowel /ɑ/ three times for six seconds each. Even though 6 to 10 trials are recommended for perturbations measures (Scherer et al., 1995) only three trials of each task were performed due to subjects' fatigue. Subjects, then, read the modified "Rainbow Passage." This modified version included three phrases from the song "America the Beautiful," so comparisons could be made between the spoken and the sung voice. Table 3-3 includes this modified version. Subjects were instructed to use a comfortable loudness, pitch and speaking rate during the above speech tasks.

Table 3-2. Voice classification and vocal training information of the subjects.

Subjects (ID)	Voice Classification	Singing Exp. Before UF (yr.)	# of Semesters at UF	Hours of practice/week
AW	Soprano	4	3	7
BM	Mezzo Soprano	1	5	5
CW	Alto	6	3	7
JD	Soprano	4	4	7
JH	Alto	3	6	15
LB	Soprano	2	3	7
MM	Soprano	3	3	11
MN	Soprano	2	3	9
RC	Soprano	4	5	7
RH	Mezzo Soprano	3	4	6
SL	Soprano	7	3	4
SG	Soprano	1	3	5
CH	Baritone	4	6	13
JP	Tenor	4	3	5

Singing tasks consisted of production of phonational range and two songs. The phonational frequency range encompassed frequencies from the lowest modal register to the highest falsetto register. Vocal fry was not included (Hollien, Dew & Phillips, 1971). A semitone chart (Appendix D) and a keyboard were used to provide reference frequencies and audiofeedback to both the researcher and the subject. To establish the lowest note, the experimenter struck A_3 and descended in a semitone order. The subject matched the tones with the sustained sung /æ/ vowel. This pitch range task was done in a step manner and performed three times to determine the low end of the phonatory range. To establish the highest note, the experimenter struck C_5 and ascended in a semitone order. The subject pitch matched each ascending tone with the same vowel. This procedure was also performed three times.

Table 3-3. Modified Version of the "Rainbow Passage."

When the sunlight strikes raindrops above the fruited plain, they act like a prism to form a rainbow. The rainbow is a division of white light into many beautiful colors. These take the shape of a long round arch, with its path high above and its ends stretching from sea to shining sea. There is according to legend, a boiling pot of gold at one end. People look but no one ever finds it unless god shed his grace on thee. When a man looks for something beyond his reach, his friends say he is looking for the pot of gold at the end of the rainbow.

Modified from Fairbanks, G. (1960). Voice and articulation drillbook (2nd ed., p.127). New York: Harper and Bros. The underlined phrases are the ones that were taken from the song "America the Beautiful".

The lowest note was the low end of the range and represented 0% of the phonational frequency range. The high end of the range represented 100% of range. Each subject sustained the /æ/ vowel at the 10, 25, 50 and 90% of his/her phonational range for six seconds.

The last task consisted on singing the first stanza of the song "America the Beautiful". During this sung task, subjects sustained the vowels of the words "sea" and "God" for four seconds, i.e. /i, ɑ/. Table 3-4 includes the singing materials.

All speaking and singing samples were recorded in a quiet environment at the Laryngeal Function Laboratory of the Institute for the Advanced Study of the Communication Processes at the University of Florida. Experimental sessions took approximately two hours. Each participant performed the tasks in a standing position. All acoustic, respiratory kinematic and EMG measurements were obtained simultaneously.

Table 3-4. First stanza of the song "America the Beautiful."

O beautiful for spacious skies. For amber waves of grain.
For purple mountain majesties. Above the fruited plain.
America! America! God shed His grace on thee,
And crown thy good with brotherhood. From sea to shining sea.

Data analysis was performed on the underlined vowels and words.

Equipment and Procedures

Acoustic Measurements

All voice productions were obtained using a high-quality cardioid head-worn type microphone (Audio-Technica, model ATM73a) positioned at a constant distance 2 cm from the right corner of the mouth (Titze & Winholtz, 1993). The samples were preamplified with a Rane MS1 amplifier. An H-P350D Hewlett-Packard attenuator was activated for loud phonations to avoid peak clipping. Voice samples were recorded to digital audiotape (DAT) using a 60ES Sony DAT recorder.

For calibration of sound pressure level (SPL), a 500 Hz tone of 80 dB SPL with a 2 cm distance from sound source to microphone was recorded onto each audiotape. Prior to measuring each subject's productions, the calibration tone was digitized and served as a reference tone calculated by Computerized Speech Lab Model 4300B (CSL, Kay Elemetrics Corp.).

Acoustic waveforms were displayed using CSL, CSL's Multi-Dimensional Voice Profile software (MDVP) and a MATLAB custom designed software – Frequency Characterization of Singer's Vibrato (FCSV) (Diaz, 1995). This last software required the Sound Blaster 16 Wave Studio to download samples from the DAT tapes to FCSV. Samples were digitized at a rate of 25.0 kHz. An antialiasing rectangular filter with a cutoff frequency of 5 kHz was used before digitization (Kent & Read, 1992; Shipp et al., 1992).

Spectral measurements and formant trajectory measurements were obtained using a CSL Model 4300B coupled to a Pentium 166 MHz computer. Some of the resulting values were converted to semitone levels (re: 16.35 Hz) because frequency is logarithmic in nature and any manipulation of the raw data (in Hertz) is subject to error (Hollien, Mendes-Schwartz, & Nielsen, 1998).

Several acoustic analyses of the speaking and singing voice were completed. Acoustic analyses of the speaking voice consisted of spectral, temporal and perturbation variables. Spectral variables included the following:

1. Mean speaking fundamental frequency (SFF1) in ST. Mean speaking fundamental frequency was defined as the average of the lowest frequency of the second sentence of the "Rainbow Passage".
2. Relative sound pressure level in dB (SPL1). Sound pressure level was defined as the amplitude of the second sentence of the "Rainbow Passage" relative to an 80 dB tone placed onto each DAT tape.

Temporal measurements were made from the modified version of the "Rainbow Passage" using the CSL. These measurements were as follows:

1. Sentence duration (seconds). Sentence duration (SD1) was computed from the second sentence of the modified "Rainbow Passage, i.e., " The rainbow is a division of white light into many beautiful colors".
2. Diphthong durations (seconds). Diphthong durations were taken from the /ɑI/ in the word "white" (DD1) and "light" (DD2). It was determined by measuring the interval of time between the onset and end of voicing (Kent & Read, 1992)
3. Closure durations of /t/ (seconds). Closure durations were measured from the acoustic interval seen in the spectrogram between the diphthong production and the release of the consonant /t/ in the word "white" (CD1) and "light" (CD2).

Perturbation measurements were obtained using the MDVP software. Perturbation analysis begins with the extraction of the F_0 and the amplitude of the voice signal. These measurements were calculated from the middle portion of the second trial of the sustained /ɑ/ vowel. (Scherer et al., 1995). The following measures were made:

1. Jitter (%). Jitter or frequency perturbation was defined as the small cycle-to-cycle variations of the fundamental frequency.
2. Shimmer (%). The shimmer or amplitude perturbation was defined as the small cycle-to-cycle variations of the peak amplitude.
3. Harmonic-to-noise ratio in dB (H/N). Harmonic-to-noise ratio measurements were done by an algorithmic analysis and were defined as the mean amplitude of the average wave from the sustained /ɑ/ vowel divided by the mean amplitude of the isolated noise components of the waves (Baken, 1987).

Acoustic analyses of the singing voice included spectral parameters, vibrato and singer's formant. Spectral analysis of the phonational ranges were calculated from the middle portion of the sustained vowel /æ/ using also the CSL. They included the following:

1. Fundamental frequency of 10% of the PFR in ST ($F_0$10).
2. Relative SPL of 10% of the PFR in dB (SPL10).
3. Fundamental frequency of 90% of the PFR in ST ($F_0$90).
4. Relative SPL of 90% of the PFR in dB (SPL90).
5. Fundamental Frequency difference between the 90% and 10% of the PFR ($F_0$90-10).
6. Relative SPL difference between 90% and 10% of the PFR (SPL90-10).

Vibrato analysis was performed with FCSV. This software uses Matlab to examine multiple parameters of the acoustic signal (Rothman, Diaz & Vincent, 1998). Two vowels were analyzed: /i/ and /ɑ/ from the words "sea' and "God", taken from the song "America the Beautiful". Vibrato variables were as follows:

1. Vibrato pulse rate (pps). Vibrato was defined as the periodic, rather sinusoidal, modulation of the F_0. Vibrato rate (frequency) specifies the number of cycles or pulses per second of this modulation.
2. Amplitude variation (dB). The amplitude of the vibrato was defined as the peak-to-peak distance during a vibrato cycle.

Lastly, the above vowels were also used to analyze the presence or absent of the singer's formant. A Fast Fourier Transform (FFT) power spectrum (Hz and dB) was performed using CSL. Three judges were asked to independently look at the FFT printout and identify the presence of the singer's formant. Only the samples with 100% agreements were included.

The secondary purpose of this project was to study the effects of the vocal training in the respiratory system. Four subjects were included in this section: AW, JP, MM and SG. Demographic and physical information were included in Table 3-1. Respiratory kinematics and EMG signals were recorded during speaking and singing tasks.

Chest Wall Kinematic Measurements

Respiratory function was sensed with linearized magnetometers (GMG Scientific, Inc., Burlington, MA) following the procedures developed by Konno and Mead (1967) and Hixon, Goldman and Mead (1973; 1976). Two pairs of magnetometers were used, each pair consisting of a generator and a sensor. One pair was placed mid-sternum to sense anteroposterior diameter changes of the rib cage. The other pair was placed 1 cm above the umbilicus for sensing anteroposterior diameter changes of the abdominal wall. All signals from the magnetometers were monitored on a storage oscilloscope (Texttronix 5111A). Signals were recorded to digital VHS tapes using a Sony SLV-750 HF data recorder coupled to a Vetter Digital model 3000A or using a Sony SLV-390 data recorder coupled to an eight-channel CRC (Instruteck, model VR 100b).

Magnetometers convert the displacements associated with the anteroposterior movements of the chest wall into a voltage output. For calibration of the voltage change produced by the magnetometers into a distance change, a calibration routine was completed after each experimental session. Each pair of magnetometers was attached with double-sided tape to plastic plates. The transmitter's plate was placed into a slotted rule at 0 cm position and kept stationary throughout the calibration procedure. The sensor magnetometer's plate was placed away from the transmitter and then was moved up and down the rule at 2 cm increments. The voltage signal produced by the magnetometers was recorded, digitized and used as a reference (Sapienza & Stathopoulos, 1994). Linearity of the calibration was computed using an automated software algorithm program within CSpeech 4.0 (Milenkovic, 1992).

Respiratory maneuvers. All measures from the linearized magnetometers were normalized for each subject's body size by asking them to perform maximum capacity maneuvers for lung volume, rib cage and abdomen (Hoit & Hixon, 1987). Maneuvers were performed three times each by the subject. The purpose was to establish consistent and reliable calibration measurements as well as to enable inferences about muscle force generation. The maneuvers included vital capacity/maximum rib cage capacity maneuvers, resting breathing, isovolume maneuvers, maximum abdominal capacity maneuvers, and relaxation maneuvers (Hixon, 1991).

Vital capacity/maximum rib cage capacity maneuvers were taken. Each subject wore a nose clip and was instructed to breathe through a mouthpiece coupled to a spirometer. From resting expiratory level, each subject inspired to total lung capacity (TLC) and expired to residual volume (RV). Three trials were performed. The largest volume expired was taken as the vital capacity. The maximum and minimum excursions defined the limits of both lung (liters) and rib cage volume (displacement). Zero percent represented the minimum lung displacement in liters and rib cage excursion in centimeters. 100% represented the maximum lung (liters) and rib cage excursion (cm) (Hixon, Goldman, Mead, 1973). Records of rest breathing were made while subjects breathed quietly for a minute after each vital capacity maneuver without equipment at the airway opening (Hixon et al., 1973).

Isovolume maneuvers were done at resting expiratory level (REL). Each subject was instructed to alternately contract and relax abdominal muscles with the glottis closed. This displaced volume back and forth between the rib cage and abdomen at a constant lung volume.

Maximum abdominal capacity maneuvers were also completed at REL against a closed glottis. It included a maximum inward and outward displacement of the abdominal wall. The maximum inward displacement represents 0% of the abdominal capacity and the maximum outward displacement represents 100% of the abdominal capacity (Hixon et al., 1973; Sapienza, 1993).

Relaxation maneuvers were performed at resting expiratory level against a closed airway. The subject was instructed to close the glottis and relax the rib cage and abdominal musculature. The resultant relaxation volume was used as a reference point, or an arbitrary zero percent point. Each initiation/termination value is positive or negative depending on whether it is higher or lower than the relaxation reference volume. For example, a positive initiation value suggests that muscular pressure was developed in an inspiratory direction (Hixon, 1991).

Samples were digitized at a sampling rate of 10 kHz. Respiratory measures of lung, rib cage and abdominal volumes were made with CSpeech and a Pentium 200 MHz computer equipped with a Data Translation analog-to-digital signal processing board (DT 2839). The following are the measures that were extracted:

Lung volume measures:

1. LVI (liters). Lung volume at which the speech or singing task was initiated.
2. LVT (liters). Lung volume at which the speech or singing task was terminated.
3. LVE (liters). Total lung volume used to complete the speech or singing task (i.e., LVT - LVI = LVE).

Rib cage measures: Rib cage displacements were sensed by the linearized magnetometers. The displacements were digitized and referenced to REL.

1. RCVI (cm). Rib cage volume initiation was defined as the degree of the displacement relative to REL at the initiation of the speech tasks.

2. RCVT (cm). Rib cage volume termination was defined as the degree of displacement relative to REL at the end of the speech task.

3. RCVE (cm). Rib cage volume excursion was defined as the degree of displacement used for a breath group (initiation-termination).

Abdominal measures: Abdominal displacements were sensed by the linearized magnetometers. The displacements were digitized and referenced to REL.

1. ABVI (cm). Abdominal volume initiation was defined as the degree of displacement relative to REL at the initiation of the speech task.

2. ABVT (cm). Abdominal volume termination was defined as the degree of displacement relative to REL at the termination of the speech task.

3. ABVE (cm). Abdominal volume excursion was defined as the degree of displacement used for a breath group (initiation-termination).

Electromyographic Measurements

Respiratory electromyographic signals (EMG) from muscles of inhalation and exhalation were collected with bipolar surface electrodes (NDM Infant ECG Surface Electrodes Item 01-5810) attached to the skin. The targeted muscles were the pectoralis major, rectus abdominis and external obliques. These muscles were chosen due to their anatomic position and their easy access to electrode placement. The dead surface layer of the skin and its protective oils were removed to lower the electrical impedance. This was done by light abrasion of the subject's skin with 70% isopropyl rubbing alcohol at the site chosen for the electrode application. The following electrode placement was selected based on previous research (Basmajian & De Luca, 1985; Kondo & Bishop, 1987; McFarland & Smith, 1989):

1. Rib cage wall: Two surface electrodes were placed between the second and the third rib on the mamillary line. This placement sampled muscle activity from the pectoralis major.
2. Abdominal medial wall: Two surface electrodes were placed 2 cm from the midline and 3 cm above the umbilicus. This placement sampled muscle activity from the rectus abdominis.
3. Abdominal lateral wall: Two surface electrodes were placed along the anterior axillary line midway between the anterior illiac crest and costal margin, 2 cm apart. This placement sampled muscle activity from the external obliques.
4. A ground electrode was placed on the right wrist for safety purposes (Baken, 1987).

All electromyographic signals were obtained using a Regulated Power Supply Grass RPS 107. Signals were filtered at 100-3 kHz and amplification gain was set at x1000. The EMG signals were monitored on a computer screen using CSpeech 4.0. They were recorded onto digital VHS tapes using a Sony SLV-750 HF data recorder coupled to a Vetter Digital model 3000A or using a Sony SLV-390 data recorder coupled to an eight-channel CRC (Instruteck, model VR 100b).

Subjects were asked to perform activation gestures in order to ensure that muscle activity was being sampled from the correct muscle group (McFarland & Smith, 1989). At the end of each experimental session a 500μV signal was recorded for calibration purposes. Electromyographic signals were analyzed with CSpeech 4.0. The following measures were performed:

1. Burst duration (milliseconds). Burst duration was defined as the time between onset of the burst of EMG activity and the termination of the burst, measured from the raw EMG signal. Onset was defined as the time at which the first positive deflection from the baseline was noted and burst offset was defined as the time the waveform returns to baseline.
2. Peak amplitude of burst (volts). The peak amplitude of the burst of EMG activity was determined from the integrated waveform. It was defined as the magnitude displacement from the baseline. Peak amplitude was expressed as a percent of the peak amplitude measured during maximum voluntary effort requiring maximal contraction of the muscle of interest. Electromyographic activity between bursts, relative to 0, was a reflection of the tonic activity of that muscle.

All chest wall kinematic measurements and EMG measurements were extracted from the following speaking and singing tasks:

1. Singing 10% and 90% levels of PFR;
2. Reading the short phrase: "…God shed his grace on thee.";
3. Reading the sentence: "People look but no one ever finds it unless God shed his Grace on thee";
4. Singing the short phrase: "…God shed his grace on thee."; and
5. Singing the sentence: "America! America! God shed his grace on thee."

Statistical Analysis

The acoustic data was analyzed using a repeated measures analysis. The primary factor was vocal training or semesters of vocal training. This quantitative factor had four levels, i.e., four semesters of vocal training. Additional factors were voice classification (sopranos, mezzo sopranos, alto, baritone, tenor), weekly hours of practice and years of singing experience prior to entering UF. As there were only two men out of fourteen subjects, gender factor was not taken into consideration.

The main advantage of a repeated measures analysis lies in its ability to reduce error variance. That is, variability among the subjects due to individual differences is completely removed from the error term. This makes this design very powerful (Stevens, 1992). This analysis is also the natural design to use when concern is with performance trends over time, as it is the case of this project.

All continuous acoustic variables were statistically analyzed using Proc Mixed of SAS. The response variables were modeled against the independent variables: vocal training, voice classification, singing experience and weekly hours of practice. If weekly hours of practice and singing experience did not significantly affect the model, then only vocal training and voice classification were retained in the model. The nominal response variable, presence/absent of singer's formant, was statistically analyzed using an exact chi-square test for each semester.

Due to small sample size, respiratory kinematic and electromyographic data were analyzed using descriptive statistics. Associations between acoustic and respiratory kinematic data as well as EMG and respiratory kinematic data were analyzed with correlation coefficients using Microsoft Excel (Version 2000).

CHAPTER 4
RESULTS

This longitudinal study investigated the effects of vocal training on the speaking and singing voices of voice major students. A secondary goal was to determine the effects of vocal training on chest wall motion and respiratory muscle force generation. The study used an incomplete repeated measures design for the acoustic data. Fourteen subjects were recorded during four consecutive semesters of vocal training. However, due to subject drop out, three subjects were not recorded in the last semester, i.e., 4th semester. The dependent variables included acoustic measures taken from speaking and singing voice productions.

The results of this investigation will be presented in the same order as found in the methodology section. Acoustic variables of the speaking voice included speaking fundamental frequency and sound pressure level of the reading tasks; and perturbation measures of sustained vowels. Temporal measures of the speaking voice included sentence duration, diphthong durations and closure duration of stop consonants. The dependent variables of the singing voice included fundamental frequency and sound pressure level of the 10% and 90% levels of the phonational range; vibrato pulses per second and vibrato amplitude variation; and the presence/absence of the singer's formant.

For all the continuous acoustic variables, a repeated measures analysis was performed using Proc Mixed of SAS. The above dependent variables were modeled against the independent variables: number of semesters of vocal training, voice classification, singing experience and weekly hours of practice. As there were only two males out of fourteen volunteers, it was not possible to include this factor in the model in order to detect sex differences. Also, singing experience and weekly hours of practice and prior singing experience were not statistically significant effects and therefore were dropped from the model. Statistical significance was established at $p< 0.05$ for all analyses reported throughout this study. Finally, descriptive analysis of within subject effects for the singing voice, as a function of vocal training per voice classification group will be presented graphically for those dependent variables that reached significance. These graphs are found in Appendix E.

The Effects of Vocal Training on the Speaking Voice

Acoustic signals of the speaking voice were recorded during four consecutive semesters of vocal training. The hypothesis regarding these effects stated that

> "The acoustic characteristics of the speaking voice within voice major students will change after four consecutive semesters of vocal training."

Spectral, temporal and perturbation variables were collected to observe the effects of four semesters of vocal training on the speaking voice. Means and standard deviations obtained from these measures are contained in Table 4-1.

Spectral measures of the speaking voice consisted of the speaking fundamental frequency (SFF1) and sound pressure level (SPL1). The repeated measures analysis revealed that vocal training did not have a significant effect on SFF1, however voice classification had a significant effect on SFF1, $F(3, 36) = 18.92, p = .0002$. A multiple comparison analysis among the five voice classification groups revealed that sopranos used significantly higher SFF1 than tenors ($p = .0003$) and baritones ($p = .0001$). Mezzo-sopranos used significantly higher SFF1 than tenors ($p = .0007$) and baritones ($p = .0002$). Altos used significantly higher SFF1 than tenors ($p = .0009$) and baritones ($p = .0003$). Neither vocal training nor voice classification had a significant affect on SPL1.

Table 4-1. Means and standard deviations for acoustic measures obtained from spoken samples during four semesters of vocal training.

Vocal Training	1st Semester		2nd Semester		3rd Semester		4th Semester	
Measures (units)	M	SD	M	SD	M	SD	M	SD
Spectral								
SFF1 (ST)	45.36	3.09	45.66	3.66	45.90	2.78	45.70	2.32
SPL1 (dB)	93.68	7.24	93.33	6.47	92.98	5.41	93.42	6.37
Temporal								
SD1 (sec.)	3.57	0.24	3.46	0.25	3.53	0.25	3.58	0.30
DD1 (sec.)	0.21	0.04	0.21	0.04	0.22	0.03	0.23	0.04
DD2 (sec.)	0.28	0.04	0.26	0.02	0.27	0.03	0.27	0.04
CD1 (sec.)	0.03	0.02	0.04	0.02	0.04	0.03	0.05	0.03
CD2 (sec.)	0.06	0.02	0.06	0.02	0.06	0.03	0.06	0.02
Perturbation								
Jitter (%)	0.88	0.71	0.69	0.82	0.68	0.73	0.66	0.63
Shimmer (%)	2.64	0.86	2.49	0.99	1.93	0.74	2.11	1.20
H/N (dB)	0.19	0.26	0.11	0.03	0.11	0.01	0.11	0.01

SFF1 = Speaking fundamental frequency; SPL1 = Speaking sound pressure level; SD1 = Sentence duration; DD1 = Diphthong duration of "white"; DD2 = Diphthong duration of "light"; CD1 = Closure duration of "white"; and CD2 = Closure duration of "light".

Temporal measures of the speaking voice included duration of sentence, diphthongs and closure of stop consonants. Repeated measures analysis revealed that vocal training or voice classification did not have a significant effect on sentence duration

(SD1). Diphthong duration in the word "white" (DD1) was not effected by vocal training but it was significantly effected by voice classification, $F(3, 36) = 6.92, p = .0104$. A multiple comparison of the five voice classification groups revealed that during reading aloud tasks, altos used significantly longer DD1 than sopranos ($p = .0013$) and baritones ($p = .0103$).

Vocal training or voice classification did not significantly effected diphthong duration of the word "light" (DD2), closure duration of /t/ in the word "white" (CD1) or in the word "light" (CD2). In order to assess the reliability of temporal measurements, intra-measurer agreements from two research assistants were taken. Correlation measures of DD1 measures were $r = .8062$, for DD2 $r = .7622$, for CD1 $r = .7152$ and for CD2 $r = 0.8814$.

Perturbation measures of the speaking voice included jitter, shimmer and harmonic-to-noise ratio. The means of the three perturbation measures tended to decrease as the number of semesters of vocal training increased. However, repeated measures analysis revealed that vocal training and voice classification did not significantly effect any of these parameters.

Table 4-2 provides the results of the repeated measures analysis with the relevant statistics and *p*-values for each dependent variable. This table shows that vocal training did not significantly effect any of the speaking acoustic variables. However, voice classification did have a significant effect on SFF1 and DD1, that is, the higher the voice classification group the higher SFF1 was used, and altos produced longer diphthong durations of the word "white" than any other voice classification group.

Table 4-2. Repeated measures analysis examining the effects of vocal training (VT) and voice classification (VC) on acoustic measures taken from spoken samples.

Measures		NDF	DDF	*F* - value	Pr > *F*
Spectral					
SFF1					
	VT	3	36	0.39	0.7038
	VC	4	9	18.92	0.0002 *
SPL1					
	VT	3	36	0.08	0.9678
	VC	4	9	0.22	0.9221
Temporal					
SD1					
	VT	3	36	0.82	0.4888
	VC	4	9	0.59	0.6812
DD1					
	VT	3	36	0.60	0.6191
	VC	4	9	6.92	0.0104*
DD2					
	VT	3	36	0.57	0.6375
	VC	4	9	0.49	0.7457
CD1					
	VT	3	36	1.75	0.1744
	VC	4	9	0.64	0.6495
CD2					
	VT	3	36	0.04	0.9882
	VC	4	9	2.11	0.1623
Perturbation					
Jitter					
	VT	3	36	0.23	0.8641
	VC	4	9	0.55	0.7046
Shimmer					
	VT	3	36	1.79	0.1673
	VC	4	9	2.14	0.1581
H/N					
	VT	3	36	1.12	0.3595
	VC	4	9	1.24	0.3551

*statistically significant at $p < .05$

Effects of Vocal Training on the Singing Voice

The hypothesis regarding the effect of vocal training on the singing voice stated that

> "The acoustic characteristics of the singing voice within voice major students will change after four semesters of vocal training".

Spectral, vibrato and singer's formant variables were collected to examine the effects of four semesters of vocal training on the singing voice. Means and standard deviations of the continuous variables are contained in Table 4-3.

Spectral measures consisted of fundamental frequency of 10% and 90% levels of the phonational range ($F_0$10 and $F_0$90, respectively). The difference between these two measures was also calculated, i.e. $F_0$90-10. The $F_0$90-10 is representative of the 10% and 90% interval of the phonational range, and all frequencies were expressed in semitones (ST). Repeated measures analysis revealed that vocal training did not have an effect on $F_0$10. However, voice classification had a statistically significant effect, $F\ (4, 9) = 19.00$, $p = 0.0002$. A multiple comparison analysis of the five voice classification groups revealed that sopranos produced significantly higher $F_0$10 than mezzo-sopranos ($p = .0412$), altos ($p = .0112$), tenors ($p = .0006$), and baritones ($p = .00001$). Mezzo-sopranos produced significantly higher $F_0$10 than tenors ($p = .0164$) and baritones ($p = .0008$). Altos produced significantly higher $F_0$10 than tenors ($p = .0385$) and baritones ($p = .0016$).

The mean of $F_0$90 increased as number of semesters of vocal training increased. Both vocal training and voice classification had a significant effect on $F_0$90, $F\,(3, 36) = 7.06, p = .008$ and $F\ (4, 9) = 22.71, p = .0001$, respectively. A multiple comparison analysis across the semesters of vocal training revealed that, when compared with the 1st semester, $F_0$90 showed a significant increase on the 3rd (*p* = .0230) and on the 4th semesters (*p* = .0001). Also, $F_0$90 values of the 2nd semester and the 3rd semester were significantly lower than the values of the 4th semester (*p* = .0011 and *p* = .0054, respectively). Sopranos produced significantly higher $F_0$90 values than tenors (*p* = .0003) and baritones (*p* = .0001). Mezzo-sopranos also had significantly higher $F_0$90 values than tenors (*p* = .0044) and baritones (*p* = .0002).

Table 4-3. Means and standard deviations for acoustic measures obtained from sung samples during four semesters of vocal training.

Vocal Training	1st Semester		2nd Semester		3rd Semester		4th Semester	
Measures (units)	M	SD	M	SD	M	SD	M	SD
Spectral								
$F_0$10 (ST)	44.03	3.03	44.25	4.27	43.74	2.97	42.71	4.18
$F_0$90 (ST)	64.13	5.36	65.38	5.24	66.41	6.10	68.51	6.10
$F_0$90-10 (ST)	20.10	3.27	21.13	5.11	22.67	3.79	25.80	3.76
SPL10 (dB)	83.10	7.91	81.27	10.68	86.10	7.28	89.59	11.68
SPL90 (dB)	99.80	5.77	105.16	9.55	107.49	14.07	116.42	12.61
SPL90-10 (dB)	16.70	9.52	23.89	12.79	21.42	9.90	26.82	6.10
Vibrato								
ffi (pps)	5.63	0.75	5.49	0.68	5.45	0.64	5.65	0.71
ffa (pps)	5.69	1.07	5.33	0.54	5.71	0.86	5.21	1.53
Avami (dB)	3.02	1.13	3.28	1.63	3.22	1.64	2.47	1.82
Avama (dB)	2.39	1.48	2.78	1.70	2.45	1.29	2.20	1.95

$F_0$10, $F_0$90 and $F_0$90-10 = Fundamental frequency of 10%, 90% and 90-10 levels of the phonational frequency range; SPL10, SPL90 and SPL90-10 = Sound pressure level of 10%, 90% and 90-10% levels of PFR; ffi = vibrato pulse rate of /i/; ffa = vibrato pulse rate of /ɑ/; Avami = vibrato amplitude variation of /i/; and Avama = vibrato amplitude variation of /ɑ/.

The range in fundamental frequency between the 90% and 10% levels of the phonational range showed a significant increase as vocal training progressed, $F(3,36) = 6.44, p = .0013$. A multiple comparison analysis across the semesters revealed that during the 4th semester $F_0$90-10 was significantly higher than the 1st ($p = .0001$), 2nd ($p = .0009$) and 3rd semesters ($p = .0083$). Voice classification had no effect on this spectral variable. Figure 4-1 presents the trends of $F_0$10, $F_0$90 and $F_0$90-10 as vocal training increased.

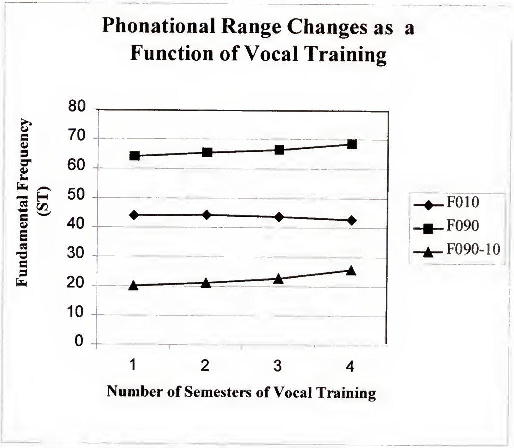


Figure 4-1. Phonational range changes as a function of vocal training. All values are in semitones.

Sound pressure level measures were taken from the sung samples of the 10%, 90% and 90-10% levels of the phonational range. Even though the means of SPL of the

10% of the phonational range (SPL10) increased as the vocal training progressed, neither vocal training nor voice classification showed a significant effect.

Sound pressure level of the 90% level of the phonational range (SPL90) increased significantly as the numbers of the semesters of vocal training increased, *F* (3, 36) = 7.67, *p* = .0004. A multiple comparison analysis across the semesters of vocal training revealed that SPL90 on the 4th semester was significantly higher than the SLP90 on the 1st (*p* = .0001), 2nd (*p* = .0016) and 3rd semesters (*p* = .0033). Also, the SPL90 mean of the 3rd semester was significantly higher than the one for the 1st semester (*p* = .0246). Voice classification did not have a significant effect on this variable.

The SPL range between the 90% and the 10% levels of the phonational range (SPL90-10) significantly increased as vocal training increased, *F* (3,36) = 3.48, *p* = .0256. A multiple comparison analysis revealed that when compared with the 1st semester, SLP90-10 showed a significant increase during the 2nd semester (*p* = .0187) and during the 4th semester (*p* = .0120). Figure 4-2 presents the trends of SPL10, SPL90 and SPL90-10 as vocal training progressed.

Vibrato variables taken from sustained sung /i/ and /ɑ/ vowels of the "America the Beautiful" included vibrato pulses per second in semitones (ffi and ffa, respectively) and vibrato amplitude variation in dB (Avami and Avama, respectively). Repeated measures analysis revealed that vocal training and voice classification did not significantly affect any of the above variables.

Table 4-4 provides the Repeated Measures Analysis table with the relevant statistics and *p*-values for each dependent continuous acoustic variable. This table shows that vocal training significantly effected $F_0$90, $F_0$90-10, SPL90 and SPL90-10.

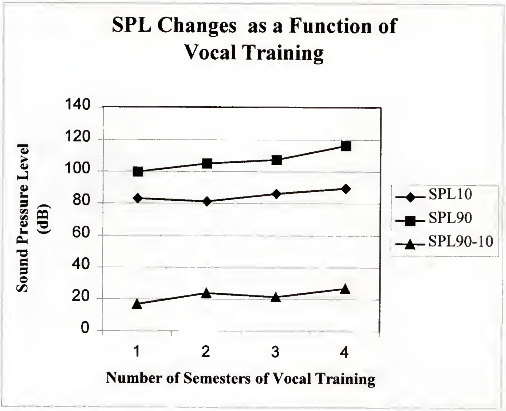


Figure 4-2. SPL changes as a function of vocal training.

Lastly, Table 4-5 shows the results of the presence or absence of the singer's formant in the sung vowels /i/ and /ɑ/. An exact chi-square test was run for each semester to see if voice classification was associated with the presence or absence of the singer's formant in each vowel.

For the vowel /i/, voice classification was not associated with the presence or absence of the singer's formant at any of the four semesters of the vocal training. For the vowel /ɑ/, voice classification was associated with the absence of the singer's formant on the third semester of vocal training, χ^2 4, N = 8.011, p = .047. This significant association revealed that for 87.5% of the sopranos, the singer's formant was absent for the vowel /ɑ/

Table 4-4. Repeated measures analysis examining the effects of vocal training (VT) and voice classification (VC) on acoustic measures taken from the sung samples.

Measures		NDF	DDF	*F* - value	Pr > *F*
Spectral					
$F_0$10					
	VT	3	36	0.47	0.7056
	VC	4	9	19.00	0.0002 *
$F_0$90					
	VT	3	36	7.06	0.0008*
	VC	4	9	22.71	0.0001*
$F_0$90-10					
	VT	3	36	6.44	0.0013*
	VC	4	9	3.38	0.0599
SPL10					
	VT	3	36	1.95	0.1386
	VC	4	9	0.11	0.9746
SPL90					
	VT	3	36	7.67	0.0004*
	VC	4	9	2.65	0.1124
SPL90-10					
	VT	3	36	3.48	0.0256*
	VC	4	9	0.85	0.5297
Vibrato					
ffi					
	VT	3	36	0.47	0.7059
	VC	4	9	0.48	0.7530
ffa					
	VT	3	36	2.25	0.0990
	VC	4	9	0.39	0.8133
Avami					
	VT	3	36	0.72	0.5477
	VC	4	9	2.39	0.1282
Avami					
	VT	3	36	0.26	0.8509
	VC	4	9	1.26	0.3552

*statistically significant at $p < .05$

on the third semester of vocal training. However, this is a weak association due to a *p* – value close to .05, small sample size and it is only observed on the 3rd semester. The rest of the semesters did not show a significant association between voice classification and the presence or absence of the singer's formant.

In summary, vocal training has a significant effect on the singing voice, specifically on F_0 and SPL of 90% level and 90-10% range of the PFR.

Table 4-5. Number of singers' formant identified by three raters.

Vocal Training	1st Semester	2nd Semester	3rd Semester	4th Semester
/i/	2	2	3	2
/ɑ/	4	3	5	2

Within subjects analysis

To determine the within subject effects for the singing voice as a function of vocal training per voice classification group a descriptive analysis was performed for the response variables that achieved significance. For the $F_0$90 variable, the within subject analysis (Appendix E, Figure E-1) revealed that for the eight sopranos, the $F_0$90 range was between approximately 64 to 74 ST during the four semesters of vocal training (VT). Seven of the eight sopranos produced the lowest tone of the $F_0$90 during their first semester. These seven sopranos showed consistent increases in their ability to produce higher tones within the $F_0$90 as vocal training progressed. For the two mezzo-sopranos and two altos, $F_0$90 ranged from approximately 62 to 72 ST during the four semesters of vocal training. For the tenor, $F_0$90 ranged from approximately 55 to 63 ST during the four semesters of VT. All mezzo-sopranos, altos and tenor produced the lowest tone of the $F_0$90 during their first semester and increased their ability to produce higher tones within the $F_0$90 as vocal training progressed. This pattern was not observed with the baritone, which presented a $F_0$90 range between 52.58 and 52.70 ST during the four semesters.

For the $F_0$90-10 variable, within subject analysis (Appendix E, Figure E-2) revealed that for the eight sopranos, the $F_0$90-10 range was from approximately 18 to 32 ST during the four semesters VT. Seven of the eight sopranos produced the lowest tone of the $F_0$90-10 during their first semester. These seven sopranos showed consistent increases within the $F_0$90-10 as vocal training progressed. The two mezzo-sopranos showed different patterns. One increased 6 ST and the other increased 9 ST as VT progressed. The two altos' $F_0$90-10 rang was between 19 and 31 ST during the four semesters of VT. They produced the lowest tone of the $F_0$90-10 during their first semester. The baritone's $F_0$90-10 variable ranged between 14 and 19 ST. The tenor's $F_0$90-10 rang was between 14 and 26 ST. His $F_0$90-10's highest tone was achieved during the last semester of VT.

For the SPL90 variable, within subject analysis (Appendix E, Figure E-3) revealed that for the eight sopranos the SPL90 ranged form approximately 81 to 125 dB during the four semesters VT. Five of the eight sopranos produced the softest tone of the SPL90 during their first semester. These five sopranos showed consistent increases within the SPL90 as VT progressed. The two mezzo-sopranos also increased SPL90 as the VT progressed with exception of the last semester where one mezzo-soprano decreased SPL90. The two altos presented the softest and the loudest tone of SPL90 during the first and last semester of VT, respectively. Both the baritone and tenor presented the loudest SPL90 during the last semester of vocal training, 108 dB and 125 dB, respectively.

For the SPL90-10 variable, within subject analysis (Appendix E, Figure E-4) revealed that for the eight sopranos the SPL90-10 ranged from approximately 5 to 42 dB during the four semesters VT. Four sopranos and all other voice classification groups produced the softest tone of the SPL90-10 during their first semester. Mezzo-sopranos' and altos' SPL90-10 ranged from approximately 5-35 dB and 10-55 dB, respectively. The baritone's SPL90-10 ranged from 10 to 25 dB during four semesters. The tenor's SPL90-10 ranged from approximately 7.5 to 22.5 dB and increased during the four semesters of vocal training.

In summary, within subject analysis revealed that in general the lowest values of $F_0$90, $F_0$90-10, SPL90 and SPL90-10 variables were produced during the 1st semester of VT. Secondly, as VT progressed subjects increased their ability to produce higher values within the above variables.

The Effects of Vocal Training on Chest Wall Movements

A secondary purpose of this project was to determine the effects of vocal training on chest wall movements during speaking and singing. Four subjects participated in this section: three females and one male with ages ranging from 18-20 years. Subjects are identified as AW, MM, SG and JP and their physical characteristics are presented in Table 3-1. Respiratory kinematic signals were recorded during three consecutive semesters of vocal training. The hypothesis stated that

> “The respiratory excursions of rib cage and abdomen wall within voice major students will change after three semesters of vocal training.”

Respiratory kinematic measures included excursion measures of lung volume (LVE), rib cage (RCE) and abdomen (ABE). These variables were extracted from three phonatory tasks, which were the following: 1) phonational frequency range (PFR), 2) read tasks, and 3) sung tasks. The dependent variables of the PFR were extracted from the 10% and 90% levels. The dependent variables extracted from the reading of the “Rainbow Passage” included one phrase, “God shed his grace on thee” and one sentence, “People look but no one ever finds it unless God shed his grace on thee”. The dependent variables extracted from the singing of the “America the Beautiful” also included the phrase “God shed his grace on thee” and the sentence “America! America! God shed his grace on thee.”

Due to the small sample size, descriptive statistics were performed for all the continuous respiratory kinematic variables. Correlation coefficients between respiratory kinematic measures and spectral measures were also performed using Microsoft Excel.

Means and standard deviations of lung volume excursion (LVE) measures extracted from 10% and 90% of the PFR, read and sung tasks, are contained in Table 4-6. Results revealed that for PFR frequency and SPL measures, LVE means decreased throughout the three-semester period of vocal training. For read tasks, LVE means decreased from the 1st to the 2nd semester and increased from the 2nd to the 3rd semester. However, for the sung tasks, LVE means increased from the 1st to the 2nd semester and decreased from the 2nd to the 3rd semester of vocal training.

LVE means increased as the demanding level and length of the phonatory task increased. That is, the 90% levels of the PFR presented larger LVE than the 10% levels.

LVE means were larger during sung than read tasks. For both phonatory tasks, sentence production presented larger LVE than phrase segments. Figure 4-3 presents the trends of LVE of PFR, read and sung tasks as the vocal training increased.

Table 4-6. Means and standard deviations for lung volume excursion measures obtained from read and sung samples during three semesters of vocal training.

Vocal Training	1st Semester		2nd Semester		3rd Semester	
Measures (liters)	M	SD	M	SD	M	SD
PFR						
10%	1.47	0.63	1.14	0.31	0.97	0.36
90%	2.11	0.30	1.69	0.39	1.66	0.62
Read						
Phrase	0.23	0.14	0.22	0.07	0.24	0.11
Sentence	0.59	0.17	0.44	0.10	0.54	0.25
Sung						
Phrase	0.99	0.22	1.46	0.71	0.79	0.36
Sentence	1.84	0.70	1.87	0.71	0.97	0.24

PFR = Phonational frequency range.

Means and standard deviations of rib cage excursions (RCE) performed during vital capacity maneuvers (VC), read and sung tasks are contained in Table 4-7. All rib cage excursion means increased from the 1st to the 2nd semester, and decreased from the 2nd to the 3rd semester of vocal training. These patterns were evident for VC, read and sung tasks. RCE means increased as the demanding level of the phonatory tasks increased. The RCE trends are presented in Figure 4-3.

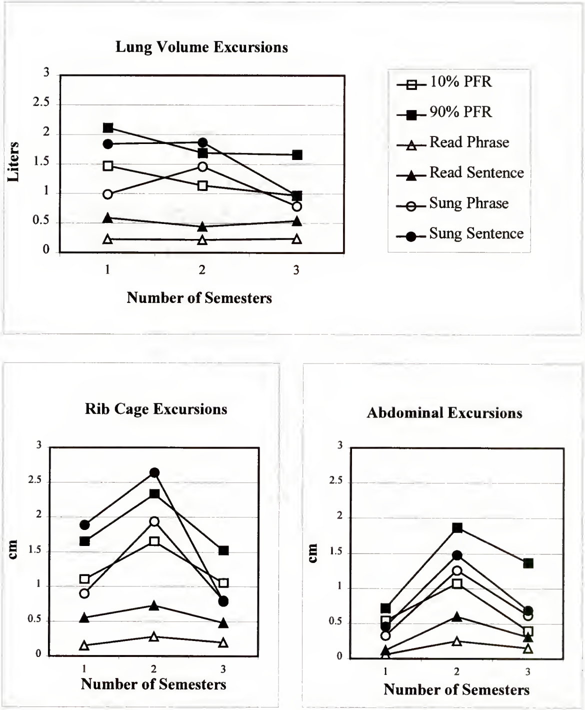


Figure 4-3. Respiratory kinematic changes as a function of vocal training.

Table 4-7. Means and standard deviations for rib cage excursion measures obtained from vital capacity maneuvers, read and sung samples during three semesters of vocal training.

Vocal Training	1st Semester		2nd Semester		3rd Semester	
Measures (cm)	M	SD	M	SD	M	SD
VC	2.85	0.86	5.56	1.17	4.03	2.77
PFR						
10%	1.10	0.34	1.65	0.62	1.05	0.58
90%	1.65	0.41	2.33	0.29	1.52	1.48
Read						
Phrase	0.15	0.12	0.28	0.20	0.20	0.08
Sentence	0.55	0.28	0.73	0.33	0.48	0.14
Sung						
Phrase	0.90	0.50	1.94	0.51	0.80	0.79
Sentence	1.89	1.65	2.64	0.75	0.79	0.47

VC = Vital capacity maneuver; and PFR = Phonational frequency range.

Means and standard deviations of abdominal excursions (ABE) extracted from VC maneuvers, read and sung samples are contained in Table 4-8. All abdominal excursion means increased from the 1st to the 2nds semester, and decreased from the 2nd to the 3rd semester of vocal training. ABE means increased as the demanding level of the phonatory tasks increased. The 90% level of PFR presented larger ABE than the 10% level; also sung samples had larger ABE than read samples. Lastly, sentence productions presented larger ABE than phrase segments. Figure 4-3 presents ABE trends.

Table 4-8. Means and standard deviations for abdominal excursion measures obtained from the vital capacity maneuvers, read and sung samples during three semesters of vocal training.

Vocal Training	1st Semester		2nd Semester		3rd Semester	
Measures (cm)	M	SD	M	SD	M	SD
VC	1.01	0.51	3.78	3.94	2.19	0.90
PFR						
10%	0.54	0.49	1.07	1.02	0.40	0.17
90%	0.72	0.59	1.87	2.26	1.32	1.03
Read						
Phrase	0.06	0.03	0.25	0.38	0.15	0.11
Sentence	0.12	0.08	0.60	1.05	0.31	0.27
Sung						
Phrase	0.33	0.40	1.26	1.49	0.62	0.61
Sentence	0.46	0.39	1.48	1.67	0.69	0.49

VC = Vital capacity maneuver; and PFR = Phonational frequency range.

The data presented in Tables 4-7 and 8 reveal that rib cage excursions typically exceeded abdominal excursions. This occurred for all phonatory tasks.

Correlation coefficients for each subject between respiratory kinematic changes and spectral changes over the three semesters of vocal training are contained in Table 4-9. The correlation coefficient (*r*) determined the type and strength of association between the respiratory kinematic and spectral changes. The larger the absolute value of *r*, the stronger the degree of association between the variables. An $r \geq \pm .80$ is considered a strong association (Agresti & Finlay, 1986; Mark, 1994; Stevens, 1992). Overall, rib

Table 4-9. Correlation coefficients between ribcage and abdominal excursion changes and spectral measure changes from read and sung samples from each subject during three semesters of vocal training.

	RCE/ F0	RCE/SPL	ABE/F0	ABE/SPL
10% of PFR				
AW	0.9842	-0.1919	0.4599	0.8862
JP	0.8910	-0.6475	-0.5345	-0.6988
MM	0.9969	-0.5775	0.9127	-0.8478
SG	0.1890	0.0038	0.9237	-0.9802
90% of PFR				
AW	-0.1112	0.7141	-0.4108	0.8945
JP	-0.8987	-0.8360	-0.6036	-0.4975
MM	-0.7362	-0.9733	0.0874	0.5640
SG	-0.6233	-0.9033	-0.9281	-0.9974
Read phrase				
AW	-0.9968	0.3866	-0.9756	0.6435
JP	-0.7924	-0.5398	-0.6201	-0.7284
MM	0.9650	0.2538	0.5074	-0.8660
SG	0.4018	0.4452	0.6595	0.6227
Read sentence				
AW	-0.2774	-0.2923	-0.4833	0.8830
JP	0.2647	-0.8433	0.3740	-0.7769
MM	0.9940	-0.9652	-0.9820	0.9412
SG	0.5285	-0.4430	-0.8316	0.0038
Sung phrase				
AW	0.6548	-0.3884	-0.4039	0.6675
JP	-0.9494	-0.5926	-0.9889	-0.7205
MM	-0.5432	-0.6776	-0.3899	-0.7945
SG	0.5551	-0.9352	-0.5843	-0.6596
Sung sentence				
AW	-0.7879	0.3286	0.1718	0.3894
JP	0.0229	-0.9786	0.1965	-0.9279
MM	-0.9916	-0.2099	-0.9884	-0.1880
SG	0.3153	-0.8987	-0.8445	-0.6430

cage excursion changes had a strong positive correlation with fundamental frequency changes at the 10% level of the PFR. RCE changes also presented a strong negative correlation with SPL changes at the 90% level of the PFR. Both trends were evident with the exception of one subject. There were other positive and negative correlations; however, they seem scattered and with no apparent trend.

In summary, from the 1st to the 2nd semester of vocal training there was an overall increase in RCE and ABE means. From the 2nd to the 3rd semester of vocal training, RCE and ABE means decreased. These patterns were observed for both the read and sung tasks. As the demanding levels and lengths of phonatory tasks increased, there was a tendency for RCE and ABE means to increase. Lastly, RCE changes over the three semesters of vocal training had an overall highly positive association with the changes in F_0 of the 10% level of PFR and a highly negative association with the SPL changes of 90% levels of PFR.

The Effects of Vocal Training on Respiratory Muscle Force Generation

The effects of vocal training on respiratory muscle force generation were examined on the same four subjects (3 females and 1 male) that participated in the respiratory kinematic section. Surface electromyographic signals (EMG) of three muscles involved in respiratory function during speech were recorded during the same three consecutive semesters of vocal training as the respiratory kinematic signals. The hypothesis stated that

> "The muscle force generation of the pectoralis major, rectus abdominis and external obliques will change within voice major students after four semesters of vocal training."

Electromyographic measures of the pectoralis major, rectus abdominis and external oblique muscles included burst duration (BD) and peak amplitude of the burst (PA). These variables were extracted from the same three phonatory tasks reported in the respiratory kinematic section, that is, PFR, read and sung tasks.

Due to a small sample size, only descriptive statistics were performed. Correlation coefficients between electromyographic measures and respiratory kinematic measures were performed using Microsoft Excel 2000. Some EMG data points are missing due to heart beat signal interference or difficulty in obtaining a good EMG signal.

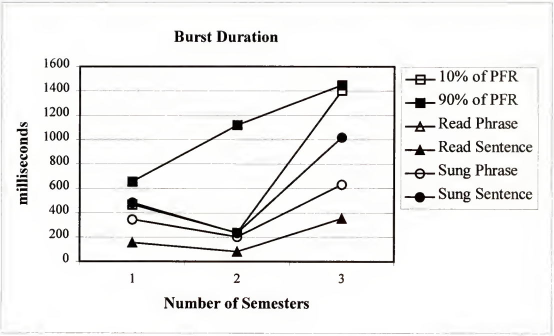
Means and standard deviations for BD and PA measures of the pectoralis major (PM) muscle obtained from three semesters of vocal training are contained in Table 4-10. Burst duration means of the PM muscle decreased from the 1st to the 2nd semester of vocal training for all phonatory tasks with the exception of one task, the 90% level of the PFR. From the 2nd to the 3rd semester, BD means increased for all phonatory tasks. Overall, burst duration means of PM increased as the demanding level and the length of the phonatory tasks increased. That is, BD was longer for the 90% level of the PFR, sung and sentence productions than for the 10% of the PFR, read and phrase productions. The only exception to this trend was observed with the reading tasks during the 1st semester, where the BD mean of the sentence ($M = 115.1$ ms) was shorter than the one for the phrase segment ($M = 154.85$ ms). These trends of PM are presented in Figure 4-4.

Peak amplitude (PA) means of the pectoralis major muscle increased from the 1st to the 2nd semester and decreased from the 2nd to the 3rd semester of vocal training. This trend was observed for all phonatory tasks. As the demanding level and length of the phonatory tasks increased all PA means of the pectoralis major also increased.

Table 4-10. Means and standard deviations of burst duration and peak amplitude measures of the pectoralis major muscle obtained from read and sung samples during three semesters of vocal training.

Vocal Training	1st Semester				2nd Semester				3rd Semester			
Measures	Burst Duration (ms)		Peak Amplitude (V)		Burst Duration (ms)		Peak Amplitude (V)		Burst Duration (ms)		Peak Amplitude (V)	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
PFR												
10%	486.10	706.02	0.32	0.04	238.55	283.65	0.76	0.50	1401.50	999.27	0.52	0.14
90%	654.03	604.84	0.46	0.19	1119.90	1282.99	1.04	0.58	1447.67	1381.56	0.78	0.41
Read												
Phrase	154.85	97.41	0.31	0.17	80.90	21.28	0.52	0.15	352.50	512.97	0.40	0.10
Sentence	115.10	51.21	0.37	0.14	93.90	27.70	0.78	0.63	678.65	1005.20	0.42	0.12
Sung												
Phrase	346.10	262.24	0.37	0.14	204.50	110.87	0.97	0.42	629.90	605.74	0.87	0.60
Sentence	482.03	153.35	0.48	0.22	234.30	114.23	1.28	0.30	1018.30	822.67	0.98	0.50

PFR = Phonational frequency range; ms = milliseconds; and V = volts.



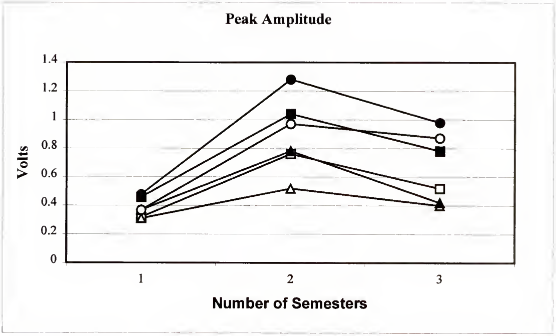


Figure 4-4. Electromyographic changes of the pectoralis major muscle as a function of vocal training.

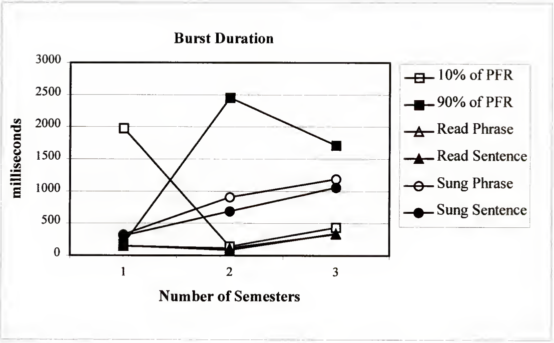
Means and standard deviations of burst duration and peak amplitude from the rectus abdominis (RA) muscle obtained from three semesters of vocal training are contained in Table 4-11. Burst duration means of the RA muscle extracted from the 10% level of the PFR and read samples decreased from the 1st to the 2nd semester and increased from the 2nd to the 3rd semester of vocal training. For the 90% level of PFR, BD means of RA muscle increased from the 1st to the 2nd semester and decreased from the 2nd to the 3rd semester. During sung tasks, the BD mean kept increasing throughout the three-semester period of vocal training. Lastly, BD means of the RA muscle were longer during sung than read tasks. However, high standard deviations were found for PFR and sung tasks. JP and SG subjects tended to contract RA almost throughout the entire phonatory production, while the other two subjects presented shorter BD, mostly at the end of the breath group.

Peak amplitude means from the RA muscle increased from the 1st to the 2nd semester of the vocal training for all phonatory tasks. From the 2nd to the 3rd semester, PA means decreased for all phonatory tasks with the exception of the 10% level of the phonational range, where PA means kept increasing. As the demanding levels of phonatory tasks increased, PA means also tended to increase, with the exception of the 3rd semester, where the PA mean of the 90% level of the PFR (M = 0.91 V) was smaller than the 10% level (M = 1.24 V). PA means also increased as the length of the phonatory tasks increased (i.e. phrases vs. sentences). Burst duration and peak amplitude trends of RA are presented in Figure 4-5.

Table 4-11. Means and standard deviations of burst duration and peak amplitude measures of the rectus abdominis muscle obtained from read and sung samples during three semesters of vocal training.

Vocal Training	1st Semester				2nd Semester				3rd Semester			
Measures	Burst Duration (ms)		Peak Amplitude (V)		Burst Duration (ms)		Peak Amplitude (V)		Burst Duration (ms)		Peak Amplitude (V)	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
PFR												
10%	1975.30	2754.36	0.42	0.24	139.70	36.14	0.90	0.14	438.83	576.07	1.24	1.18
90%	174.03	52.40	0.77	0.29	2452.30	2024.33	1.05	0.28	1712.70	1645.27	0.91	0.39
Read												
Phrase	148.38	114.00	0.32	0.24	83.40	21.55	0.49	0.31	339.00	333.90	0.49	0.31
Sentence	146.75	108.95	0.33	0.24	112.95	55.96	0.99	0.49	331.50	295.85	0.61	0.30
Sung												
Phrase	325.23	278.52	0.73	0.09	905.95	625.46	1.30	0.70	1187.50	1227.85	1.08	0.45
Sentence	304.70	280.82	0.89	0.26	685.90	706.15	1.51	0.50	1059.10	1661.50	1.23	0.79

PFR = Phonational frequency range; ms = milliseconds; and V = volts.



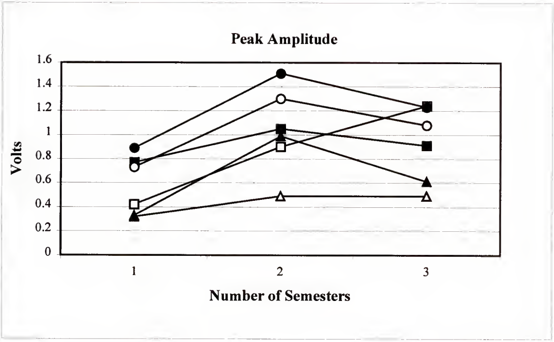


Figure 4-5. Electromyographic changes of the rectus abdominis muscle as a function of vocal training.

Means and standard deviations of burst duration and peak amplitude from the external oblique (EO) muscle obtained from three semesters of vocal training are contained in Table 4-12. Burst duration means of the EO muscle extracted from the 10% level of the PFR and read samples decreased from the 1st to the 2nd semester and increased from the 2nd to the 3rd semester of vocal training. However, for high demanding phonatory tasks such as the 90% level of the PFR and sung tasks, BD means of EO kept increasing throughout the three semesters of vocal training

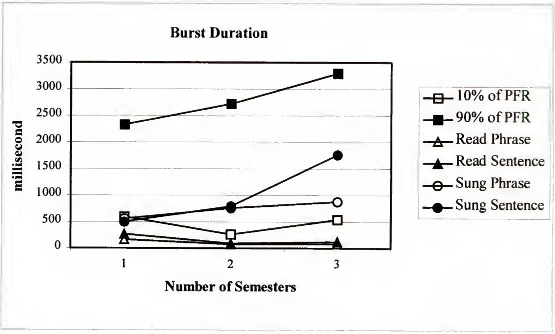
Burst duration means tend to increase as the demanding levels and the length of the phonatory tasks increased, with exception of the 1st semester of vocal training where the BD mean of the sung phrase (M = 558.8 ms) is longer than the BD mean of the sung sentence (M = 495.9 ms).

Peak amplitude means of the external oblique muscle increased from the 1st to the 2nd semester and decreased from the 2nd to the 3rd semester of vocal training. This pattern was observed for all phonatory tasks. PA means also increased as the demanding level and the length of the phonatory tasks increased, with exception of the 3rd semester where the PA mean of the sung sentence (M = 0.83 V) is smaller than the PA mean of the sung phrase (M = 0.84 V). Burst duration and peak amplitude trends of EO are presented in Figure 4-6.

Table 4-12. Means and standard deviations of burst duration and peak amplitude measures of the external oblique muscle obtained from read and sung samples during three semesters of vocal training.

Vocal Training	1st Semester				2nd Semester				3rd Semester			
Measures	Burst Duration (ms)		Peak Amplitude (V)		Burst Duration (ms)		Peak Amplitude (V)		Burst Duration (ms)		Peak Amplitude (V)	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
PFR												
10%	594.30	379.01	0.36	0.15	261.30	325.20	0.80	0.51	539.90	264.89	0.67	0.41
90%	2326.30	3255.00	0.61	0.24	2726.30	3009.18	1.25	0.97	3293.43	2405.48	0.71	0.32
Read												
Phrase	163.60	63.60	0.28	0.07	74.95	23.04	0.82	0.55	78.63	28.52	0.53	0.25
Sentence	265.10	155.13	0.30	0.05	89.60	24.35	1.49	1.83	120.30	44.76	0.56	0.20
Sung												
Phrase	558.83	451.22	0.62	0.14	759.50	786.27	1.17	0.53	881.70	1349.49	0.84	0.19
Sentence	495.90	483.52	0.96	0.54	797.05	1148.21	1.76	1.17	1757.10	3058.98	0.83	0.20

PFR = Phonational frequency range; ms = milliseconds; and V = volts.



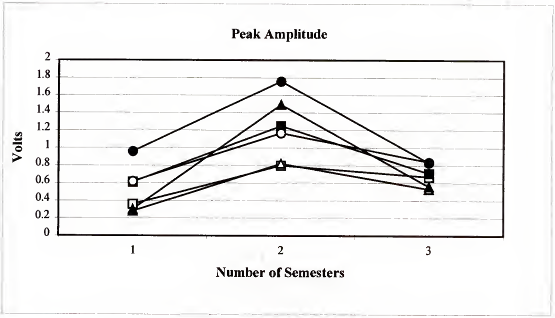


Figure 4-6. Electromyographic changes of the external oblique muscle as a function of vocal training.

Correlation coefficients (*r*) between respiratory kinematic changes (rib cage and abdominal excursions) and electromyographic measure changes (burst duration and peak amplitude) from each subject are contained in Table 4-13. The cutoff considered to indicate of a strong association was set up at $r = \pm .80$. There are several missing correlations points due to missing of EMG data points.

Overall, burst duration and peak amplitude measures from the pectoralis major muscle had greater correlations with the respiratory kinematic measures than did the rectus abdominis or the external oblique muscles. Peak amplitude measures of the PM presented frequent positive strong associations with RCE measures for all phonatory tasks, with exception of the sung sentence tasks. Burst duration of PM presented frequently negative associations with the ABE measures. One perfect negative correlation ($r = -1$) was observed for subject MM during read phrase tasks.

The rectus abdominis' peak amplitude measures presented frequent strong positive associations with RCE measures for all phonatory tasks, with the exception of the read phrase task. One perfect correlation ($r = +1$) was observed for subject JP for the 90% level of the PFR.

The external obliques' burst duration presented frequent strong positive associations with ABE measures and negative correlations with RCE. Other correlations were scattered and with no visible trends.

In summary, burst duration of PM, RA and EO muscles decreased from the 1st to the 2nd semester and increased from the 2nd to the 3rd semester of vocal training. Peak amplitude of the three muscles increased from the 1st to the 2nd semester and decreased from the 2nd to the 3rd semester of vocal training. Overall BD and PA of the above muscles increased as the demanding level and the length of the phonatory tasks increased. Pectoralis major and rectus abdominis presented strong positive associations with rib cage excursions while external obliques presented strong positive associations with the abdominal excursions.

Table 4-13. Correlation coefficients between respiratory kinematic changes and electromyographic measure changes obtained from read and sung samples from each subject during three semesters of vocal training.

	Pectoralis Major				Rectus Abdomins				External Obliques			
	RCE/BD	RCE/PA	ABE/BD	ABE/PA	RCE/BD	RCE/PA	ABE/BD	ABE/PA	RCE/BD	RCE/PA	ABE/BD	ABE/PA
10% of PFR												
AW	0.7191	0.9892	0.8708	0.1408	-0.0886	0.9989	-0.9801	0.3297	-0.9629	0.8589	-0.5327	-0.2466
JP	0.1085	-0.9743	-0.9999	-0.1339					0.9480	-0.9829	-0.4045	0.2741
MM	-0.5334	0.7865	-0.8185	0.4873	-0.5208	0.8801	-0.8099	0.6287	-0.9922	0.7082	-0.9634	0.3810
SG	-0.3058	0.3801	-0.8709	0.8293	-0.7568	-0.1708	0.7928	-0.9306				
90%of PFR												
AW	0.9280	0.5555	0.9976	0.2734	-0.2035	0.1279	0.1068	-0.1827	-0.4448	-0.2323	-0.1485	-0.5196
JP	-0.8150	-0.1917	-0.4729	0.2641	0.1160	1.0000	0.5451	0.8948	0.2006	-0.3221	0.6148	0.1318
MM												
SG	-0.9885	0.9504	-0.9342	0.6730	-0.3205	-0.5666	-0.7464	-0.0860	-0.6293	-0.2286	-0.1636	0.2818
Read Phrase												
AW	-0.8380	-0.7146	-0.6378	-0.8904					-0.9986	-0.2311	-0.9376	-0.5101
JP	-0.8936	0.6554	-0.9760	0.4520					-0.9546	0.3057	-0.9984	0.0649
MM	-0.2672	0.9572	-1.0000	-0.0266	-0.2530	0.7246	-0.9999	-0.4737	-0.2760	0.7938	0.8543	-0.3773
SG	0.1909	0.9912	0.8084	-0.2995	-0.1495	-0.5724	0.9591	0.9852				
Read Sentence												
AW	0.9529	-0.5000	-0.8883	-0.2589					-0.8754	-0.4559	0.9608	-0.3071
JP	-0.6049	0.4630	-0.6914	0.5606					-0.5253	0.0088	-0.6185	0.1222
MM	-0.2414	0.9950	0.1625	-0.9837	-0.6047	0.9874	0.5387	-0.9969	-0.6445	1.0000	0.7039	-0.9971
SG	-0.5309	0.9994	0.1342	-0.9245	-0.8615	-0.9587	0.5754	0.7560				
Sung Phrase												
AW	0.3624	0.6573	-0.6881	0.9621	0.6681	0.8278	-0.3876	-0.1538	0.5754	0.8222	0.9852	-0.1636
JP	-0.9993	0.9293	-0.9783	0.9784	-0.1602	0.9887	0.0092	0.9998	-0.1737	0.7137	-0.0044	0.8220
MM												
SG	-0.8644	-0.5516	-0.7740	-0.9746	-0.8507	-0.8905	-0.7906	-0.7384	-0.1149	-0.8887	0.8900	0.1178
Sung Sentence												
AW	0.8032	-0.9954	-0.9953	0.8031	0.9911	-0.1355	-0.6461	-0.5637	-0.6970	0.2626	0.9979	-0.1636
JP	-0.9905	0.7195	-0.9515	0.8293	-0.5699	0.9941	-0.4183	0.9978	-0.3420	0.7069	-0.1734	0.8220
MM												
SG	-0.8353	0.6658	-0.7355	-0.5629	0.1374	-0.6161	-0.9279	-0.9133	-0.8447	0.0994	-0.7237	0.1178

RCE =Rib cage excursions; ABE = Abdominal excursions; BD = Burst durations; and PA = Peak amplitude.

CHAPTER 5
DISCUSSION

The primary purpose of this longitudinal study was to investigate the acoustic effects of four semesters of vocal training on the speaking and singing voices of voice majors. Additional objectives were to determine the effects of three semesters of vocal training on chest wall motion and respiratory muscle force generation during spoken and sung tasks. Because vocal classification factor was not a concern of this study, it will only be reported when a significant effect was observed.

The findings of this study will be discussed in the order of the research questions posed. First, is there a difference in the functioning of the laryngeal system in voice majors after four semesters of vocal training that can be detected in the acoustic signal? Second, is there a difference in the functioning of the articulatory system in voice majors after four semesters of vocal training that can be detected in temporal measures? Third, is there a difference in the movements of the rib cage and abdomen in voice majors after three semesters of vocal training that can be detected in respiratory kinematic signals? And fourth, is there a difference in the muscle force generation of the pectoralis major, the rectus abdominis, and the external oblique muscles in voice majors after three semesters of vocal training that can be detected in EMG signals? For each question, the discussion that follows will include related studies previously reported in the review of the literature, interpretations drawn from the statistical analysis, and possible explanations for the patterns observed.

Many cross-sectional studies have compared the speaking and singing voice of singers and nonsingers. These studies reported that the acoustic and physiological differences found between these two groups were the result of vocal training. However, these studies did not actually examine the effects of vocal training. This is the first longitudinal investigation that examines the direct effects of vocal training on voice majors.

The Effects of Vocal Training on the Speaking Voice

The effects of vocal training on the speaking voice were examined by measuring acoustic variables of spoken and read samples produced by fourteen voice majors during four consecutive semesters. The results of this investigation revealed that vocal training did not have a significant effect on spectral, temporal and perturbation measures extracted from the speaking voice. This finding is not surprising, given that vocal training mostly targets the singing voice and rarely the speaking voice.

Although four semesters of vocal training did not have a significant effect on the speaking voice of these subjects, a few trends associated with speaking fundamental frequency (SFF) and perturbation measures were noted. The mean SFF increased as vocal training progressed. There was a slight increment of 1 ST (i.e., 16 Hz) during the four semesters of vocal training. Previous studies that compared SFF between singers and nonsingers reported that singers, as a group, have a 1 to 4 ST higher SFF than nonsingers.

However these differences were not statistically significant (Brown et al., 1990, 1991, 1993).

The results of the present longitudinal study agreed with the previous cross-sectional investigations and confirmed that there is a tendency for singers, even in early stages of college vocal training, to start using a higher SFF. The slight changes of SFF toward the higher frequencies are probably a consequence of the isotonic-isometric vocal function exercises. These exercises are designed to strength the laryngeal musculature, especially the cricothyroid muscle that is involved in raising fundamental frequency. Additionally, these exercises also help to increase laryngeal efficiency by achieving a complete and symmetrical glottal closure, thereby affecting the balance of the transglottal air pressure and its resulting airflow. Ultimately, these exercises are practiced with the goal of achieving the highest frequency possible during singing. However, these shifts appeared to be reflected in the speaking voice.

Perturbation values of the speaking voice, which included jitter, shimmer and harmonic-to-noise ratio, decreased as vocal training progressed. Previous research that compared professional singers to nonsingers, reported that professional singers have lower perturbation values than nonsingers (Brown et al., 1990, 1997; Murry et al., 1978, 1979). The present longitudinal study confirmed the findings of the previous cross-sectional studies. But more important, the present study demonstrated that the decrements of the perturbation measures start to show during the early stages of college vocal training. This is probably a consequence of vocal function exercises, which may seem to reduce vocal fold irregularities due to variations in the mass, tension and muscle as well as to improve vocal fold coordination, which might be reflected in the speaking voice.

Although vocal training did not have a significant effect on the speaking voice, voice classification had a significant effect on SFF and diphthong duration of the word "white". Sopranos, mezzo-sopranos and altos used a significantly higher SFF than tenors and baritones. This finding is not surprising since sopranos, mezzo-sopranos and altos are all females and tenors and baritones are all males. Therefore, the appropriate SFF differences found here result from the sex dependent anatomical and physiological differences in the laryngeal system of the subjects. The myoelastic-aerodynamic theory reports that less massive and thinner vocal folds, like the ones found in females, vibrate at higher rates than the more massive and thicker ones, which are found in males (van den Berg, 1956).

Temporal measures taken from the spoken samples included duration of the second sentence of the "Rainbow Passage", diphthong durations from the words "white" and "light" and closure durations from /t/ of the same words. Surprisingly, voice classification had a significant effect on the diphthong duration of the word "white". That is, altos produced significantly longer diphthongs in the word "white" than did sopranos and baritones. At this juncture, no apparent compelling theoretical and practical reasons emerge to explain this finding.

In the present study no significant effects or trends were observed in temporal measures derived from the spoken samples as a function of four semesters of vocal training. In concert with previous cross-sectional studies that compared temporal measures from the same spoken samples of singers and nonsingers (Brown et al., 1997; Rothman et al., 1998), the results of the present study, which focused on the characteristics of the voice majors over time provide further confirmation that vocal training does not seem to effect the articulatory system, at least in spoken samples. One would expect, however, that articulatory shifts would be found in the sung samples, at least in the practiced songs. One of the areas of vocal training focuses on the over articulation of the last phoneme of phrases and/or sentences. The objective of over articulating these segments is to improve the singing intelligibility for the listeners.

Lastly, as was the case for the data concerning SFF, vocal training did not have a significant effect on the sound pressure level (SPL) of the second sentence of the "Rainbow Passage". No SPL trends emerged from four semesters of vocal training. Even though vocal training targets the increase of vocal amplitude in the singing voice, this is not seen in the speaking voice. Previous research that compared speaking SPL between professional singers and nonsingers revealed that singers, as a group, speak at significantly higher vocal intensities than nonsingers (Brown et a., 1993). The present longitudinal study has not revealed any increase of SLP as a function of vocal training in spoken productions. One possibility is that this trend shows up in more advanced stages of vocal training and that four semesters of training are not enough for SPL increments to be reflected in the speaking voice.

In summary, the findings of this study revealed that four semesters of vocal training had no significant effect on the speaking voice of voice majors. This finding was expected given the research literature (e.g., Brown et al., 1990, 1991), which suggested that many years of singing experience are needed in order to detect differences in the spoken voice. However, examination of the speaking fundamental frequency and perturbation data revealed that there were certain patterns developing as a function of the vocal training. These were the following: SFF slightly increased as the number of semesters of vocal training increased and perturbation measures decreased as vocal training progressed.

Several implications can be extrapolated from these findings. Vocal performers and pedagogues should not expect changes to the speaking voice as a function of four semesters of vocal training, as results of this study clearly show that four semesters of vocal training had no effect on the speaking voice. Speech-language pathologists (SLP) involved in the vocal care of singers should be aware that vocal training techniques do not automatically generalize or transfer to the speaking voice. The findings of this study may guide the SLP towards counseling the singer regarding expectations of the rehabilitation of vocal pathology. The voice scientist should be aware that even though the same three anatomical systems (i.e., respiratory, laryngeal and supralaryngeal) are used for the production of the speaking and singing voices, vocal training exercises mostly involving the singing voice do not affect the speaking voice, at least to the same degree. That is, physiologically these systems seem to behave differently in the production of speaking and singing voices, at least after being exposed to only four semesters of vocal training.

The Effects of Vocal Training on the Singing Voice

The effects of vocal training on the singing voice were examined by measuring acoustic variables of sung samples produced by fourteen voice majors during four consecutive semesters. The results of this investigation revealed that vocal training had a significant effect on the singing voice, specifically on the phonational frequency range (PFR).

Four semesters of vocal training had a significant effect on the fundamental frequency at the 90% level of the PFR ($F_0$90). $F_0$90 increased significantly by 4 ST during this vocal training period. Also, the range in fundamental frequency between the 90% and the 10% levels ($F_0$90-10) increased significantly by 5.7 ST. That is, $F_0$90-10 was 20.10 ST in the 1st semester and increased to 25.80 ST in the 4th semester of vocal training.

Within subject analysis revealed that, in general, all voice classification groups produced the lowest values of $F_0$90 and $F_0$90-10 during the 1st semester. These groups increased their ability of producing higher values within the above variables as vocal training progressed. This means that voice majors exposed to vocal training appear to be able to enhance their singing F_0 capabilities. It would seem that the vocal training (VT) that these voice majors are engaged in is effectively enhancing control over the laryngeal musculature and aerodynamics necessary for frequency control, and, in particular, the cricothyroid muscle.

Previous studies that analyzed the PFR between professional singers and nonsingers generally compared the 0% and 100% levels of the PFR. These studies reported that singers, as a group, have a significantly wider PFR than nonsingers. That is, singers' PFR can go up to 45 ST, while nonsingers' PFR only go to 29.1 ST (Åkerlund et al., 1992). This larger singers' PFR is, generally found towards the higher frequencies (Brown et al., 1993).

The results of the present longitudinal study confirm the findings of the above cross-sectional studies that compared singers versus nonsingers, in that singers develop a larger PFR, especially towards the higher frequencies. But more importantly, the present results show that this effect can be seen with only four semesters of college vocal training. This increase of the PFR is probably a consequence of the more efficient use of the respiratory and laryngeal systems. During vocal training, voice majors practice respiratory exercises in order to increase strength and coordination of the inspiratory and expiratory muscles involved in singing. These exercises include posture of the rib cage and rapid manipulations of the abdominal muscles. The objective is to be able to generate the high subglottal air pressures needed for the production of high frequencies with minimum effort of the laryngeal system. Hollien, Brown and Hollien (1971) reported that regulation of F_0 in the falsetto register is more closely associated with aerodynamic factors than the myoelastic properties of the vocal folds. However, isotonic-isometric vocal function exercises also participate in the increase of the PFR. These exercises focus primarily on strengthening of the cricothyroid muscle, which when contracted, increases the length of the vocal folds and therefore increases their vibratory motion. The interaction of these two mechanisms (i.e., respiratory and laryngeal) may help to achieve the larger PFR.

The results of this study also revealed that four semesters of vocal training had a significant effect on the sound pressure level at the 90% level of the PFR (SPL90). SLP90 increased significantly by 16.62 dB from the 1st to the 4th semester of vocal training. Secondly, the SPL range between the 90% and the 10% levels (SPL90-10) increased significantly by 10.12 dB from the 1st to the 4th semester of vocal training.

Within subject analysis revealed that, in general, all the voice classification groups tend to produce the lowest values of SPL90 and SPL90-10 during the 1st semester. These groups increased their ability of producing higher values within the above variables as VT increased. This means that voice majors exposed to VT appeared to be able to increase their singing SPL capability. It seems that the VT, particular to these voice majors, is effectively enhancing the control over the respiratory and laryngeal system.

Previous studies that compared SPL of the PFR between singers and nonsingers reported that singers produced PFR 10 dB higher than nonsingers (Åkerlund et al., 1992). The results of the present longitudinal study confirm the above cross-sectional study, in that singers develop a PFR with high SPL. Moreover, this study shows that these changes develop during the early stages of the voice majors' vocal training. As was the case of $F_0$90 and $F_0$90-10, this finding must rely on the singer's ability to develop higher subglottal air pressures by achieving a high coordination between the laryngeal and respiratory musculature. Additionally, isotonic-isometric vocal function exercises, by strengthening the adductory muscles, increase complete glottal closure as well medial compression. The resultant increase in glottal resistance associated with high subglottal air pressure generated by the respiratory system assists in achieving the high SPL productions needed during singing.

Four semesters of vocal training did not have a significant effect on the fundamental frequency and sound pressure level at the 10% level of the phonational range, $F_0$10 and SPL10 respectively. However, a few trends were noted in the above two variables. The $F_0$10 mean decreased by 2.32 ST and SPL10 mean increased by 6.49 dB from the 1st to the 4th semester of vocal training.

Previous research that analyzed the 0% of the PFR between singers and nonsingers reported that singers' PFR was 1 to 2 ST lower than nonsingers. Also, singers produced these lower frequencies 5dB higher than nonsingers (Åkerlund et al., 1992; Brown et al., 1993).

The present longitudinal study shows that with four semesters of vocal training singers start to develop this ability of producing lower frequencies of the PFR at higher SPL. It is likely that this is due to the vocal function exercises and the increasing ability of voice majors to manipulate their laryngeal musculature. For example, by contracting the thyroarytenoid muscle one is increasing the mass of the vocal folds and therefore lowering their vibratory motion.

The lack of statistical significance of vocal training affect on the $F_0$10 and SLP10 variables may be due to the fact that these changes may involve a finer coordination of the respiratory and laryngeal systems than the $F_0$90 and SLP90 variables. For example, in order to produce low frequencies, vocal folds are shorter and thicker and its mode of vibration is physiologically constrained by the vocal fry mode of vibration, which is excluded from the PFR. Additionally, it seems that vocal training frequently targets more higher than lower frequencies as well as louder rather than softer productions. Therefore, four semesters of vocal training may be not enough time to show a change in the lower frequencies productions.

Vocal classification had significantly affected $F_0$10 and $F_0$90 levels of the PFR. For the $F_0$10, sopranos produced higher $F_0$10 than the other four classification groups. Also, mezzo-sopranos and altos produced higher $F_0$10 than tenors and baritones. For the $F_0$90, sopranos and mezzo-sopranos produced higher $F_0$90 than tenors and baritones. Previous studies that compared singers to nonsingers reported that there is a prominent trend for the sopranos, at least, to shift their PFR towards the higher frequencies and became differentiated from the other classification groups (Brown et al., 1993). The present longitudinal study not only confirms this trend but also shows that this trend starts during the early years of college vocal training. Also, this study reveals that the hierarchies of voice classification groups start to be acoustically differentiated during the first four semesters of vocal training, not only for the sopranos but also for the other classification groups.

It seems that there is an anatomical and/or physiological predisposition that is reinforced through vocal training. For example, before vocal training begins, voice teachers will listen to the student's voice and classify the student, for example, as a soprano. Although there is no evidence, one might speculate, that sopranos may have less massive vocal folds than the other groups, thereby enabling them to produce PFR levels that are naturally higher than the other groups. Further, as vocal training progresses, sopranos' training is directed towards the higher frequencies, therefore reinforcing the natural tendency to produce these higher frequencies. Isotonic-isometric vocal function exercises are frequently practiced throughout the voice lessons. These exercises may increase the strength or control of the cricothyroid muscle, which is responsible for increasing the fundamental frequency. Exercises associated with less massive and thinner vocal folds help the singer to more easily achieve the higher frequencies. Therefore by using these vocal exercises, singers develop a range that is predetermined by the anatomical characteristics of their laryngeal system.

Four semesters of vocal training did not have an effect on vibrato frequency and amplitude measures. Vibrato frequency range of the sung vowels /i/ and /ɑ/ were between 5.45-5.65 pulses per second during the four semesters of vocal training. Previous research that analyzed the vibrato in professional singers reported that the singers' vibrato frequency were between 4.5 and 6.5 pulses per second and a mean variation of 3% above and below the mean. (Rothman, 1987; Sapir & Larson, 1993; Titze, 1994). The present longitudinal study revealed that vibrato frequencies of the voice majors were well within the optimal ranges since the first semester of vocal training. However, vibrato pulse rate was not stable throughout the four semesters of training. Standard deviations were up to 0.75 pulses per second, that is, mean variation was 13.27% above and below the mean pulse per second rate.

The present study also reveals that vibrato amplitudes of the sung vowels /i/ and /ɑ/ ranged from 2.2 dB to 3.28 dB during four semesters of vocal training. No trends emerged as vocal training increased. Previous studies on the vibrato amplitude of professional singers reported that the optimal vibrato amplitude was 2-10 dB. The present longitudinal investigation reveals that vibrato amplitudes produced by voice majors during four semesters of vocal training were at the lower end of the optimal range. This means, that even though voice majors already have some sort of vibrato ability during the early years of vocal training, four semester of vocal training are not sufficient to develop a stable vibrato production. The most attractive explanatory approach to vibrato production involves the coordination of the cricothyroid and thyroarythnoid muscles (Shipp et al., 1990; Titze, 1994). It is probable that the coordination of these muscles is developed at later stages of the vocal training. Further research in vibrato and its stabilization for production is warranted.

Lastly, the presence or absence of the singer's formant derived from the sung vowel /i/ and /ɑ/ were analyzed and identified based on voice classification. Voice classification was significantly associated with the absence of the singer's formant in the third semester of vocal training. That is, 83.5% of the sopranos did not have the singer's formant on the third semester of vocal training. Previous research that analyzed the singer's formant in professional singers reported that sopranos do not seem to have this extra formant (Åkerlund et al., 1992; Sundberg 1974, 1987; Weiss & Morris, 1996). The present longitudinal investigation actually reveals that by the 3rd semester of vocal training sopranos decreased their ability to produce this formant, at least in the vowel /ɑ/. Even though this significance was not observed for the vowel /i/, there is a trend for the presence of the singer's formant in sopranos to decrease as the numbers of semesters of vocal training increased (Table 5-1).

This decrease in the presence of the singer's formant in sopranos is due to articulatory maneuvers. The production of the singer's formant is the result of lowering the larynx and widening the bottom of the pharynx resulting in this extra formant centered around 3000 Hz. Sopranos, on the other hand, in an effort to produce high fundamental frequencies with higher SPL, increase the size of their oral cavity aperture. This causes the first formant to be raised and approximated with the fundamental frequency, which triggers an increase in SPL up to 30 dB. Females, generally, have a 3rd formant located at approximately the same frequency as the singer's formant. Vowel modification, especially as singing fundamental frequency increases, would cause the singer's formant to decrease in amplitude because there would be no harmonic energy in the area of a formant peak to be maximized.

Table 5-1. Presence of singers' formant and voice classification groups.

Vocal Training	1st Semester		2nd Semester		3rd Semester		4th Semester	
Vowels	/i/	/ɑ/	/i/	/ɑ/	/i/	/ɑ/	/i/	/ɑ/
Sopranos	2	3	2	3	2	1	1	1
Mezzo Sopranos						1		
Altos				1		2		1
Tenors			1	1	1	1	1	
Baritones	1		1	1	1		1	1

One would expect that the other voice classification groups (i.e., altos, tenors and baritones) experienced an increase in their ability to produce the singer's formant as vocal training progressed. However, this was not observed in this longitudinal study, at least consistently. It seems that four semesters of vocal training are not enough time for the voice majors to develop the articulatory skills necessary for the production of the singer's formant.

In summary, the findings of this study revealed that four semesters of vocal training have a significant affect on the singing voice. Fundamental frequency and SPL of the 90% and 90-10% range of the PFR increased significantly as vocal training increased. This is probably due to a more efficient use and coordination of the respiratory and laryngeal systems gained during the training period. Singer's formant in the sopranos was significantly absent in the third semester of vocal training. This is due to articulatory maneuvers that sopranos perform in order to produce high fundamental frequencies with higher SPL.

Several implications can be extrapolated from these findings. Vocal performers and pedagogues should expect changes in the frequency and SPL of the PFR as a function of vocal training. The results of the present investigation clearly show that four semesters of vocal training have an effect on the PFR, especially toward the higher frequencies. Voice teachers should expect that sopranos reduce their ability to produce the singer's formant by the third semester of vocal training as they develop other articulatory maneuvers in order to obtain higher SPL at high frequencies. Lastly, four semesters of vocal training do not seem to be enough time to enhance vibrato skills, and singer's formant qualities in mezzo-sopranos, altos, tenors and baritones.

Speech-language pathologists involved in the vocal care of singers should be aware that singers develop larger frequency and SPL ranges in their PFR during their college vocal training. However, these shifts are not reflected in the speaking voice. For example, if during the interview process, a singer presents with misuse or abusive vocal behaviors and is enrolled in vocal training, the SLP should not assume that the vocal training would improve the singer's speaking voice. Furthermore, voice therapy approaches should be used to rehabilitate the speaking voice.

The voice scientist should be aware that four semesters of vocal training seems to have an effect on the respiratory, phonatory and articulatory systems involved in the production of the singing voice. This effect is reflected in the acoustic signal. The increased exercise of the respiratory and phonatory systems during four semesters of vocal training appears reflected in the PFR increase towards the higher frequencies and

SPL. Lastly, this study provides further confirmation that manipulating the articulatory system is the key for the production of the singer's formant, and that widening the jaw to produce higher SPL by adjusting the F_1 upward to tune with F_0, reduces the ability of sopranos to produce the singer's formant.

The Effects of Vocal Training on Chest Wall Movements

The secondary purpose of this project was to determine the effects of vocal training on chest wall movements. These effects were examined by measuring lung volume, rib cage and abdominal excursions extracted from read and sung samples produced by four subjects during three semesters of vocal training. Due to the small sample size, generalizations from these data should be made with caution.

The results of the present study revealed that lung volume, rib cage and abdominal excursions changed during three semesters of vocal training. The most prominent trends were observed with the rib cage and abdominal excursions (RCE and ABE, respectively).

RCE and ABE increased from the 1st to the 2nd semester and decreased from the 2nd to the 3rd semester of vocal training. These trends were observed for all phonatory tasks. The RCE and ABE increments were expected, at least for the sung tasks. Previous research that examined the respiratory kinematics in classical singers during spoken, read and sung tasks revealed that singers continuously adjusted rib cage and abdominal wall while singing (Watson & Hixon, 1985). The findings of the present longitudinal study confirmed the above cross-sectional study, but, moreover, showed that the RCE and ABE increments start to be evident by the 2nd semester of college vocal training.

One surprising fact was that RCE and ABE decreased from the 2nd to the 3rd. semester of vocal training. One possible explanation is the washout effect. That is, the second recordings of chest wall movements were made during the spring semester, which is followed by the summer where none of the voice majors received vocal training. The third recording was done after this three-month period of no training, which can account for the decrease in RCE and ABE measures. This reveals the importance of a continuous vocal training program in order to maintain achieved progress.

Another possible explanation for these decrements of RCE and ABE after the 2nd semester of vocal training may involve a more efficient usage of the respiratory and laryngeal systems. That is, as vocal training progresses, subjects develop a higher control of the respiratory movements by performing less effortful excursions of the rib cage and abdomen, which associated with a complete glottal closure, helps them to obtain the desired lung volumes needed to achieve higher subglottal air pressures. Furthermore, voice majors probably develop a finer coordination between chest wall movements and laryngeal adjustments in order to obtain the needed subglottal air pressures. For example, Stathopolos and Sapienza (1993) reported that nonsingers' laryngeal adjustments for higher intensities included a faster adductory movement and longer adductory period. It is not inconceivable then, that singers perform the same adjustments associated with reduced or more efficient respiratory adjustments.

This study also revealed that rib cage excursions constantly exceeded abdominal excursions for all reading and singing tasks. This was in agreement with previous investigations. Winkworth, Davis, Adams and Ellis (1994, 1995) analyzed respiratory kinematics during spoken and read tasks in nonsingers. These authors reported that rib cage was the predominant contributor to lung volume changes during speech productions. Also, Watson and Hixon (1985) reported that singers' rib cages were largely expanded during sung tasks, not only during inspiration, but also during phonation, in order to generate and maintain high negative subglottal air pressures needed for continuous airflow.

There are several advantages to the use of the rib cage over the abdomen. First, the rib cage is in contact with a larger portion of the surface of the lungs (about three fourths) than is the abdomen/diaphragm (about one fourth). Therefore, the movements of the rib cage need to be far less extensive than those of the abdomen/diaphragm. Second, the inspiratory muscles of the rib cage are smaller in size, faster acting, greater in number, and more richly endowed proprioceptively than those of the abdomen including the diaphragm muscle. This enables the rib cage to maintain a finer control over inspiratory and expiratory efforts than is found for the abdomen.

Even though the rib cage is the main contributor for lung volume changes, this was not observed in this study. Lung volume excursions (LVE) did not show the same definitive trends throughout the three semesters of vocal training as the RCE, or for that matter, the ABE. During the read phrase and sentence tasks, LVE decreased from the 1st to the 2nd semester and increased from the 2nd to the 3rd semester of vocal training. During the sung phrase and sentence tasks, LVE increased from the 1st to the 2nd semester and decreased from the 2nd to the 3rd semester of vocal training. Lastly, for the PFR tasks, LVE decreased throughout the entire three-semester period of vocal training.

These findings were surprising, since LVE should follow the pattern of the RCE, due to its large contributions to the LVE. Only during the sung tasks did the LVE follow the RCE. At this point, it is unclear as to why the LVE did not follow the RCE pattern for the other phonatory tasks.

The present study reveals that LVE, RCE and ABE increased as the demanding level and the length of the phonatory tasks increased. These findings were in concert with previous investigations that examined the respiratory kinematics during read tasks (Winkworth et al. 1994), spontaneous tasks (Winkworth et al., 1995) and sung tasks (Watson & Hixon, 1985; Hixon et al., 1973). These studies concluded that as the demanding levels and lengths of the phonatory tasks increased, LVE, RCE and ABE increased, too.

The present longitudinal study not only confirms previous cross-sectional studies but also shows that this trend is evident during three semesters of vocal training. This means, that as the demanding levels and the lengths of the phonatory tasks increase the respiratory system, is able to anticipate them and respond appropriately to support their aerodynamic demands. This can be seen throughout the three semesters of vocal training. It seems that there is a relatively sophisticated neural planning of the respiratory system, in anticipation of the demands and lengths of the phonatory tasks. Furthermore, Davis, Zhang, Winkworth and Bandler (1996) reported that

> The periaqueductal gray matter (PAG) is a crucial brain site for mammalian voice production, not only in the production of emotional or involuntary sounds, but also as a generator of specific respiratory and laryngeal motor patterns essential for human speech and song. (p. 23)

The present study revealed two relevant associations between respiratory kinematic and spectral measures for each subject. First, there were frequent negative associations between RCE and SPL90, and secondly, there were frequent positive associations between RCE and $F_0$10 of the PFR.

The negative associations between RCE and SPL90 changes of the PFR revealed that as the SPL90 increased, RCE decreased. One possible explanation is that by decreasing the RC volume, one increases the subglottal air pressure, creating a higher pressure differential and therefore increasing the airflow and power, i.e. the power of the voice which is measured in SPL.

On the other hand, RCE and $F_0$10 of the PFR had frequent positive associations, suggesting that as RCE increased $F_0$10 of the PFR increased, too. This is probably due to the fact that, for the production of lower fundamental frequencies, one needs to reduce the airflow rates. By increasing the volume of the rib cage, subglottal pressure decreases, as well as the transglottal pressure differential and consequently airflow rate.

In summary, the findings of this study revealed that during three semesters of vocal training LVE, RCE and ABE changed. RCE and ABE increased from the 1st to the 2nd semester and decreased from the 2nd to the 3rd semester of vocal training. RCE constantly exceeded ABE for all phonatory tasks, revealing the importance of the RCE not only for inspiratory purposes but also for posture in order to work against high relaxation pressures in order to provide the high subglottal air pressures required for singing. Lastly, LVE, RCE and ABE increased as the demanding levels and lengths of the phonatory tasks increased. This seems to be related to the amount of volume necessary to produce a spoken or sung sample. This assisted in initiating and maintaining the subglottal pressures needed for each phonatory task.

Several implications can be extrapolated from these findings for singers, vocal pedagogues, SLP and voice scientists. First, vocal performers and pedagogues should expect that rib cage and abdominal excursions change during the college vocal training years. In order to maintain the RCE and ABE changes, vocal training should be continuous, i.e., without an interval of months where no training occurs. Singers and singing teachers should also be aware that the rib cage provides a larger contribution for lung volume changes during singing than does the abdomen.

Speech-language pathologists involved in the rehabilitation of vocal pathology in singers and nonsingers should be aware that the rib cage has a greater contribution than abdomen, not only for the singing but also for the speaking voice. This finding may guide the SLP towards specific therapeutic exercises designed to improve breath efficiency for speech production purposes. Also if a SPL wishes to evaluate the respiratory function during voice production, than the type of task chosen is important, as interpretation of the results will be different as a function of the task produced (e.g., sung tasks were performed with larger RCE than read tasks).

Voice Scientists should be aware that the respiratory system appears to be highly responsive to vocal training. Only one semester of vocal training was able to increase RCE and ABE during spoken and sung tasks. Due to the fact that this study could only provided descriptive statistics in this respiratory kinematic section, further research is warranted in this area in order to provide significant evidence of the effects of vocal training on the respiratory system.

The Effects of Vocal Training on the Respiratory Muscle Force Generation

The effects of vocal training on the respiratory muscle force generation of the pectoralis major, rectus abdominis and external oblique muscles were examined by measuring the peak amplitude (PA) and burst duration (BD) extracted from spoken and sung samples produced by four subjects during three consecutive semesters. Due to the small sample size, generalizations from this section should also be made with caution.

The present study revealed that the burst of the pectoralis major muscle (PM) was present most often during inspiration or at the beginning of the breath group. An interesting finding of the present study was that the peak amplitude not only presented a strong positive association with RCE but also presented the same trend as the RCE throughout vocal training, i.e. they both increased from the 1st to the 2nd semester and decreased from the 2nd to the 3rd semester. This trend may support the hypothesis that the pectoralis major, as an accessory inspiratory muscle has a large contribution not only in lifting up and posturing the rib cage but also has a checking action to counteract the relaxation pressures (Basmajian, 1985; Zemlin, 1998). If so, the pectoralis major muscle helps to generate the high negative subglottal air pressures that, when encountering a resistance at the glottic level or any other point of the vocal tract, create high airflow rates. These high subglottal air pressures and airflows are required for the production of the high frequencies and amplitudes acoustically observed in sung samples.

The burst of the rectus abdominis muscle (RA) was most often observed at the end of the breath group, which is in agreement with Draper et al. (1959). Surprisingly, the peak amplitude of the rectus abdominis demonstrated the same trend with the RCE as the pectoralis major muscle did. That is, the peak amplitude changes of the RA muscle had a positive correlation with the RCE. Both presented an overall increase from the 1st to the 2nd semester and a decrease from the 2nd to the 3rd semesters of the vocal training. This finding seems to support Watson and Hixon's (1985) idea that, during singing, the rectus abdominis has a lesser importance for active expiration and a greater importance for rib cage postural purposes.

The burst of the external oblique muscles (EO) tended to begin at the middle of each breath group and increased activity toward the end of the phonatory task. This agrees with Draper et al. (1959). These authors reported that, at low lung volumes, expiratory activity needs to be supplemented by the external obliques in order to maintain phonation. Leanderson et al. (1987) and Watson et al. (1989) have pointed out that during singing there is an increase in the peak amplitude of the external obliques. This was confirmed in the present longitudinal study, at least for the singing tasks. There was an increase of PA from the 1st to the 2nd semesters of vocal training. At the 10% and 90% levels of PFR there was an increase of 0.44 and 0.36 volts, respectively. From the sung phrases and sentences, there was an increase of 0.55 and 0.8 volts, respectively. However, overall PA decreased from the 2nd to the 3rd semesters of vocal training. Again, this may be due to the washout effect from the summer semester where no vocal training was administered. The second possible explanation may reflect a more efficient usage of muscle force. That is, as vocal training progresses, there is less need to generate muscle force to manipulate the respiratory system, which it is probably, due to an increase in coordination with the laryngeal system.

In summary, muscle force generation of the pectoralis major, rectus abdominis and external oblique muscles increased from the 1st to the 2nd semesters and decreased from the 2nd to the 3rd semester of vocal training. The first two muscles seem to have an influence on the posture of the rib cage, while the last one seems to have a more expiratory role.

Even though the surface EMG technique has several limitations due to the contamination of signals from neighboring muscles and movement artifacts, the longitudinal findings from this study seem to be consistent with the findings from the respiratory kinematic section. That is, muscle force generation of the pectoralis major, rectus abdominis and external obliques increased from the 1st to the 2nd semesters and decreased from the 2nd to 3rd semesters of vocal training. These increment and decrement patterns during vocal training were also observed in RCE and ABE.

There are some implications that can be generated from these findings. Singers and vocal pedagogues should be aware that the increased motions of the rib cage and abdomen achieved with vocal training is due to an increase of the muscle force of specific muscles. The use of the imagery approach supplemented with anatomic and physiological knowledge of the respiratory system could help the singer to better manipulate the respiratory system.

Voice scientists have long been aware of the musculature involvement in the manipulation of the respiratory system. This study provides further evidence that the pectoralis major not only is an accessory inspiratory muscle but also is involved in the checking action to counteract relaxation pressures. Also, the rectus abdominis presented the same patterns as the pectoralis major, thereby confirming its role in maintaining rib cage posture. Further research is warranted in this area to confirm descriptive trends.

Generalization of Findings

This research not only contributes to the understanding of the longitudinal effects of vocal training, but it also has several practical implications. For example, the information derived from the present study contributes to the understanding of the developmental changes that a singer's voice goes through when exposed to an extensive period of vocal training. This information is relevant for singers, vocal pedagogues, SLP and others that deal with the training and care of the professional voice. One can expect that, as vocal training progresses, PFR will increase, not only in its frequency, but also in its amplitude. These increments should be associated with changes in chest wall movement and related respiratory musculature as well as a more efficient coordination between laryngeal and respiratory systems.

This study, like much of the contemporary research literature in respiratory kinematics, disproves the "myth of singing from the diaphragm". Rib cage excursions presented larger contributions for spoken and sung productions than did the abdomen. Even though vocal pedagogy has been changing in regard to this concept, the use of instrumentation such, as magnetometers, can provide a real-time visual feedback of the respiratory movements. This approach could be more efficient than the traditional auditory and proprioceptive biofeedback. As pointed out by Watson and Hixon (1985), it seems reasonable to assume that voice majors and/or singers, who have an accurate conceptualization about respiratory function, would be in a better position to use the respiratory apparatus more efficiently and, therefore, to influence/improve their performance.

Strengths and Limitations

Strengths

This study was designed to investigate the impact of vocal training on the respiratory, phonatory and articulatory systems of voice majors. Many studies (e.g., Åkerlund et al., 1992; Brown et al., 1990, 1991, 1993; Rothman et al., 1998; Hixon et al., 1973; Watson et al., 1989) have compared singers to nonsingers, as a group, in order to determine what makes a singer's voice different from a nonsinger's voice. All these studies are cross-sectional in nature and reported that the main factor contributing to the vocal differences between these two populations is the result of vocal training. But none actually studied the effects of vocal training. This is the first longitudinal study that examined the direct effect of vocal training on the speaking and singing voice.

By performing a longitudinal study one can begin to gain an understanding of the direct effects of vocal training over time. Also, a longitudinal study is a more powerful research design with reduced error of variance than a cross-sectional study (Marks, 1994; Stevens, 1992; Ventry & Schiavetti, 1986). This study not only confirmed the results of previous investigations that compared singers to nonsingers, but also showed the acoustic and respiratory trends that voice majors go through when exposed to extensive vocal training.

Limitations

Subjects consisted of a volunteer sample recruited from only one university and one voice program. One might ask if this is a representative sample from the universe of interest. Secondly, in both acoustic and physiological sections of the present study, sample sizes are small, N=14 and N=4 respectively. Caution should be applied to the interpretation and generalization of the findings.

Although a longitudinal study is a powerful research design, it also has its limitations. For example, one of the limitations faced in this study was the high subject drop out rate. Several subjects dropped out of this research project, primarily because of the two-hour duration required for each recording session. Secondly, during experimental sessions there were six signals being recorded simultaneously and at times it was difficult to control all of them due to time constraints and subject fatigue, which led to several attritions (i.e., loss of data).

The biggest limitation of this study may have been the washout effect that the summer semester had on this longitudinal investigation. From May to August, none of the subjects had vocal training. One would expect that some of the achievements obtained during the two preceding semesters were somewhat decreased or washed-out during the three months without vocal training.

Another possible limitation was the variability in the time intervals between consecutive recording sessions for each semester. For example, one subject was first recorded at the beginning of the Fall semester and then at the end of the Spring semester, while an other subject was recorded at the beginning of both semesters. This factor was not possible to control due to the volunteer subjects' schedules.

Future Research Questions

The present study serves as a starting point for research of the singing voice directed at the acoustic and physiological analyses of the longitudinal effects of vocal training on the respiratory, phonatory and articulatory systems of voice majors. Overall, the findings of this study revealed the need for further investigation, not only in the acoustic but also in the physiological arena. For example, significant differences were not found in the temporal and perturbation measures of the speaking voice. However, one might ask if there are differences in the temporal and perturbation measures of the singing voice as a function of vocal training.

It would be useful to replicate this study with a bigger sample size and in a university setting that would provide vocal training throughout the summer semester. The objective would be that a continuous trend of the acoustic and physiological signals could be examined. Also, voice classification groups should be equally balanced in order to observe changes in each classification group.

The present study revealed the need for further investigation of the involvement of the respiratory system during vocal training. Since this system is the driving force for vocal production, chest wall movements and respiratory muscle force generation should continue to be examined using respiratory kinematic and electromyographic techniques.

Future research will include a perceptual study where the singing voice produced by voice majors will be judged by singing teachers and nonsingers. The objective is to observe how well perceptual measures correlate with acoustic measures, and secondly, how one perceives the improvements obtained in the singing voice as a function of vocal training.

Summary and Conclusions

It is clear that vocal training has an effect on the phonatory and respiratory systems during the act of singing. For many years researchers have investigated the acoustic and physiological differences between singers and nonsingers and have been concluding that the differences observed between these two groups are the result of vocal training (e.g., Åkerlund et al., 1992; Brown et al., 1990, 1991, 1993; Rothman et al., 1998; Hixon et al., 1973; Watson et al., 1989). However, these studies have not directly examined the effects of vocal training on a group of singers. The current investigation is the first longitudinal study that directly examined the effects of vocal training. Results clearly revealed that vocal training has a significant effect on the singing voice, specifically, on the phonational range. These effects are associated with changes in the respiratory system, specifically, on chest wall movements. This study also demonstrated that the rib cage and abdominal excursion changes are associated with muscle force generation of the pectoralis major, rectus abdominis and external oblique muscles.

This investigation clearly demonstrates the effectiveness of vocal training in voice majors at the college level. The implications of the findings of the present study are also discussed as they relate to singers, vocal pedagogues, speech-language pathologists, and voice scientists.

APPENDIX A
INFORMED CONSENT FORM

INFORMED CONSENT

Project: Longitudinal tracking of vocal acoustic and respiratory biomechanic changes during vocal training of singers.

Principal investigators: Ana P. Mendes-Schwartz, M.A., Doctoral student, (352)873-2899

Supervisors: Howard Rothman, Ph. D., (352) 392-2113; and
Christine M. Sapienza, Ph.D., (352) 392-2041

Thank you for volunteering to participate in this study. The purpose of this form is to give you a written description of the study and to have you sign this informed written consent. Speaking and singing are sophisticated ways of communication. We are interested in recording samples of your speaking and singing voice during this and subsequent semesters so we can gain a better understanding of the changes in the vocal and respiratory systems and the effectiveness of vocal training.

In order to accomplish this we will ask you to speak and sing. You will stand up through the entire experiment. Your speech and singing will be recorded as well as the movements of your rib cage and abdomen and the activities of respiratory muscles. The respiratory measures will evaluate how far the rib cage and abdomen move during speaking and singing activities. The activity of your muscles will be recorded using electromyographic techniques to determine which muscles are contracting during your speech and singing.

A head-worn microphone will be placed on your head. The microphone will be placed approximately 2 cm from the corner of your mouth. Linearized magnetometers will be used to measure the movements of your rib cage and abdomen. Magnetometers consist of two pairs of coils or magnets which are taped with double-sided scotch tape at the level of your rib cage and abdomen. As you breath the rib cage and abdomen move. These movements will be measured by the magnetometers. The muscle activity of your rib cage and abdominal muscles will be measured using surface electrodes. They consist of a sticky pad that is placed on your skin. The pad has a small metal button to which we attach a wire that amplifies the muscle signal. The entire experiment should take approximately half an hour.

There will be no personal identifying information about you recorded to the tape. These tapes will be kept in a locked cabinet in 43 Dauer Hall at the University of Florida. Only the principal investigators involved in this study, and graduate students assisting with the project, may have access to your tape. Furthermore, your name will never be used with presentation or publication of data. Data will be kept confidential to the extent provided by law.

Approved by the
University of Florida
Institutional Review Board
(IRB 02) for use through
NOV 2 1 1997

In conducting our research we are always careful to safeguard our participants against harm. No one has ever been injured during the many years of our research program. As a benefit, you will have access to objective measures of acoustic and physiologic progress that are occurring as your vocal training continues. No other compensation is available for your participation. Finally, we want to inform you that you can withdraw your consent and discontinue your participation in the project at anytime without penalty. If you have any questions or concerns please feel free to contact any of the investigators referred at the beginning of this form.

Questions or concerns about research participants' rights can be directed to the UFIRB office, P0 Box 112250, University of Florida, Gainesville, FL - 32611-2250

I have read the procedure described above. I voluntarily agree to participate in the procedure and I have received a copy of the description.

SIGNATURES:

Participant Date

Principal Investigator Date

Witness Date

Approved by the
University of Florida
Institutional Review Board
(IRB 02) for use through
NOV 21 1997

APPENDIX B
VOCAL HEALTH AND BACKGROUND QUESTIONNAIRE

Name. ______________________________________

(last name, first name)

Subject Identification: _ _ _ _ _

Date: _ _ / _ _ / _ _
mo da yr

VOCAL HEALTH AND BACKGROUND QUESTIONNAIRE

(You do not have to answer any question you do not wish to answer)

1 Your age at last birthday? _ _ years DOB _ _/_ _/_ _
mo da yr

2. Please indicate gender (circle one) F M

3. Height _-_ _ in Weight _ _ _ lbs

4. Is English your first language? 1. Yes 2. No

5. Do you smoke? 1. Yes 2. No

6. Have you had any history of voice problems? 1. Yes 2. No

7 Have you had any history of speech-language problems? 1. Yes 2. No

8. Have you had any history of respiratory problems? 1. Yes 2. No

9 Have you had any history of hearing problems? 1. Yes 2. No

10. Please rate your general physical health as: 1. Excellent 2. Good 3. Fair 4. Poor

11. Do you have a cold at this time? 1. Yes 2. No

12. Do you have allergies at this time? 1. Yes 2. No

13. Your voice type is: 1. Soprano 2. Alto 3. Tenor 4. Baritone 5. Bass

14 Number of years of supervised singing activities before UF: _ _ years

15. Number of completed semesters of vocal training at UF: _ _ semesters Started: _ _/_ _/_ _
mo da yr

16. Type of vocal training: *(More than one response can be given)*

1. Women's Choir
2. University's Choir
3. Chamber's Choir
4. Voice studio
5. Other

17. How long are your lessons in hours/week?

1. Women's Choir _ _ _ hours/week
2. University's Choir _ _ _ hours/week
3. Chamber's Choir _ _ _ hours/week
4. Voice studio _ _ _ hours/week
5. Other _ _ _ hours/week

Total # _ _ _ _ hours/week

18. Total number of years of professional singing experience: _ _ years

Thank you for your time and interest

Please do not write in this space

APPENDIX C
TABLE TO DETERMINE SAMPLE SIZE

Table Sample sizes required to test $H_0: \mu_1 = \mu_2$ for various α and power

		α		POWER (%)						
Row	*DELTA*	*1-Tail*	*2-Tail*	50	60	70	80	90	95	99
1	0.100	0.050	0.10	271	361	471	620	857	1083	1578
2	0.100	0.025	0.05	385	490	618	786	1051	1300	1838
3	0.100	0.005	0.01	661	797	958	1165	1484	1777	2399
4	0.125	0.050	0.10	174	231	302	397	548	693	1010
5	0.125	0.025	0.05	246	314	396	503	673	832	1177
6	0.125	0.005	0.01	423	511	614	746	950	1138	1535
7	0.150	0.050	0.10	121	161	210	276	381	482	702
8	0.150	0.025	0.05	171	218	275	350	467	578	817
9	0.150	0.005	0.01	294	355	426	518	660	790	1066
10	0.175	0.050	0.10	89	118	154	203	280	354	516
11	0.175	0.025	0.05	126	160	202	257	343	425	601
12	0.175	0.005	0.01	216	261	313	381	485	581	784
13	0.200	0.050	0.10	68	91	118	155	215	271	395
14	0.200	0.025	0.05	97	123	155	197	263	325	460
15	0.200	0.005	0.01	166	200	240	292	371	445	600
16	0.225	0.050	0.10	54	72	94	123	170	214	312
17	0.225	0.025	0.05	76	97	122	156	208	257	364
18	0.225	0.005	0.01	131	158	190	231	293	351	474
19	0.250	0.050	0.10	44	58	76	100	137	174	253
20	0.250	0.025	0.05	62	79	99	126	169	208	295
21	0.250	0.005	0.01	106	128	154	187	238	285	384
22	0.275	0.050	0.10	36	48	63	82	114	144	209
23	0.275	0.025	0.05	51	65	82	104	139	172	244
24	0.275	0.005	0.01	88	106	127	155	197	235	318
25	0.300	0.050	0.10	31	41	53	69	96	121	176
26	0.300	0.025	0.05	43	55	69	98	117	145	205
27	0.300	0.005	0.01	74	89	107	130	165	198	267
28	0.325	0.050	0.10	26	35	45	59	82	103	150
29	0.325	0.025	0.05	37	47	59	75	100	124	174
30	0.325	0.005	0.01	63	76	91	111	141	169	228
31	0.350	0.050	0.10	23	30	39	51	70	89	129
32	0.350	0.025	0.05	32	40	51	65	86	107	151
33	0.350	0.005	0.01	54	66	79	96	122	146	196
34	0.375	0.050	0.10	20	26	34	45	61	77	113
35	0.375	0.025	0.05	28	35	44	56	75	93	131
36	0.375	0.005	0.01	47	57	69	83	106	127	171
37	0.400	0.050	0.10	17	23	30	39	54	68	99
38	0.400	0.025	0.05	25	31	39	50	66	82	115
39	0.400	0.005	0.01	42	50	60	73	93	112	150
40	0.425	0.050	0.10	15	20	27	35	48	60	88
41	0.425	0.025	0.05	22	28	35	44	59	72	102
42	0.425	0.005	0.01	37	45	54	65	83	99	133
43	0.450	0.050	0.10	14	18	24	31	43	54	78
44	0.450	0.025	0.05	19	25	31	39	52	65	91
45	0.450	0.005	0.01	33	40	48	58	74	88	119
46	0.475	0.050	0.10	12	16	21	28	38	48	70
47	0.475	0.025	0.05	18	22	28	35	47	58	82
48	0.475	0.005	0.01	30	36	43	52	66	79	107
49	0.500	0.050	0.10	11	15	19	25	35	44	64
50	0.500	0.025	0.05	16	20	25	32	43	52	74
51	0.500	0.005	0.01	27	32	39	47	60	72	96
52	0.525	0.050	0.10	10	14	18	23	32	40	58
53	0.525	0.025	0.05	14	18	23	29	39	48	67
54	0.525	0.005	0.01	24	29	35	43	54	65	88
55	0.550	0.050	0.10	9	12	16	21	29	36	53
56	0.550	0.025	0.05	13	17	21	26	35	43	61
57	0.550	0.005	0.01	22	27	32	39	50	59	80
58	0.575	0.050	0.10	9	11	15	19	26	33	48
59	0.575	0.025	0.05	12	15	19	24	32	40	56
60	0.575	0.005	0.01	20	25	29	36	45	54	73
61	0.600	0.050	0.10	8	11	14	18	24	31	44
62	0.600	0.025	0.05	11	14	18	22	30	37	52
63	0.600	0.005	0.01	19	23	27	33	42	50	67
64	0.625	0.050	0.10	7	10	13	16	22	28	41
65	0.625	0.025	0.05	10	13	16	21	27	34	48
66	0.625	0.005	0.01	17	21	25	30	38	46	62
67	0.650	0.050	0.10	7	9	12	15	21	26	38
68	0.650	0.025	0.05	10	12	15	19	25	31	44

Table *(continued)*

		α		POWER (%)						
Row	*DELTA*	*1-Tail*	*2-Tail*	50	60	70	80	90	95	99
69	0.650	0.005	0.01	16	19	23	28	36	43	57
70	0.675	0.050	0.10	6	9	11	14	19	24	35
71	0.675	0.025	0.05	9	11	14	18	24	29	41
72	0.675	0.005	0.01	15	18	22	26	33	39	53
73	0.700	0.050	0.10	6	8	10	13	18	23	33
74	0.700	0.025	0.05	8	10	13	17	22	27	38
75	0.700	0.005	0.01	14	17	20	24	31	37	49
76	0.725	0.050	0.10	6	7	9	12	17	21	31
77	0.725	0.025	0.05	8	10	12	15	20	25	35
78	0.725	0.005	0.01	13	16	19	23	29	34	46
79	0.750	0.050	0.10	5	7	9	12	16	20	29
80	0.750	0.025	0.05	7	9	11	14	19	24	33
81	0.750	0.005	0.01	12	15	18	21	27	32	43
82	0.775	0.050	0.10	5	5	8	11	15	19	27
83	0.775	0.025	0.05	7	9	11	14	18	22	31
84	0.775	0.005	0.01	11	14	16	20	25	30	40
85	0.800	0.050.	0.10	5	5	8	10	14	17	25
86	0.800	0.025	0.05	7	8	10	13	17	21	29
87	0.800	0.005	0.01	11	13	15	19	24	28	38
88	0.825	0.050	0.10	4	5	7	10	13	16	24
89	0.825	0.025	0.05	6	8	10	12	16	20	28
90	0.825	0.005	0.01	10	12	15	18	22	27	36
91	0.850	0.050	0.10	4	5	7	9	12	15	22
92	0.850	0.025	0.05	6	7	9	11	15	18	26
93	0.850	0.005	0.01	10	12	14	17	21	25	34
94	0.875	0.050	0.10	4	5	7	9	12	15	21
95	0.875	0.025	0.05	6	7	9	11	14	17	25
96	0.875	0.005	0.01	9	11	13	16	20	24	32
97	0.900	0.050	0.10	4	5	6	8	11	14	20
98	0.900	0.025	0.05	5	7	8	10	13	17	23
99	0.900	0.005	0.01	9	10	12	15	19	22	30
100	0.925	0.050	0.10	4	5	6	8	11	13	19
101	0.925	0.025	0.05	5	6	8	10	13	16	22
102	0.925	0.005	0.01	8	10	12	14	18	21	29
103	0.950	0.050	0.10	3	4	6	7	10	12	18
104	0.950	0.025	0.05	5	5	7	9	12	15	21
105	0.950	0.005	0.01	8	9	11	13	17	20	27
106	0.975	0.050	0.10	3	4	5	7	10	12	17
107	0.975	0.025	0.05	5	5	7	9	12	14	20
108	0.975	0.005	0.01	7	9	11	13	16	19	26
109	1.000	0.050	0.10	3	4	5	7	9	11	16
110	1.000	0.025	0.05	4	5	7	8	11	13	19
111	1.000	0.005	0.01	7	8	10	12	15	18	24
112	1.025	0.050	0.10	3	4	5	6	9	11	16
113	1.025	0.025	0.05	4	5	6	8	10	13	18
114	1.025	0.005	0.01	7	8	10	12	15	17	23
115	1.050	0.050	0.10	3	4	5	6	8	10	15
116	1.050	0.025	0.05	4	5	6	8	10	12	17
117	1.050	0.005	0.01	6	8	9	11	14	17	22
118	1.075	0.050	0.10	3	4	5	6	8	10	14
119	1.075	0.025	0.05	4	5	6	7	10	12	16
120	1.075	0.005	0.01	6	7	9	11	13	16	21
121	1.100	0.050	0.10	3	3	4	6	8	9	14
122	1.100	0.025	0.05	4	5	6	7	9	11	16
123	1.100	0.005	0.01	6	7	8	10	13	15	20

APPENDIX D
FREQUENCY RANGE OF THE VOICE AND INSTRUMENTS

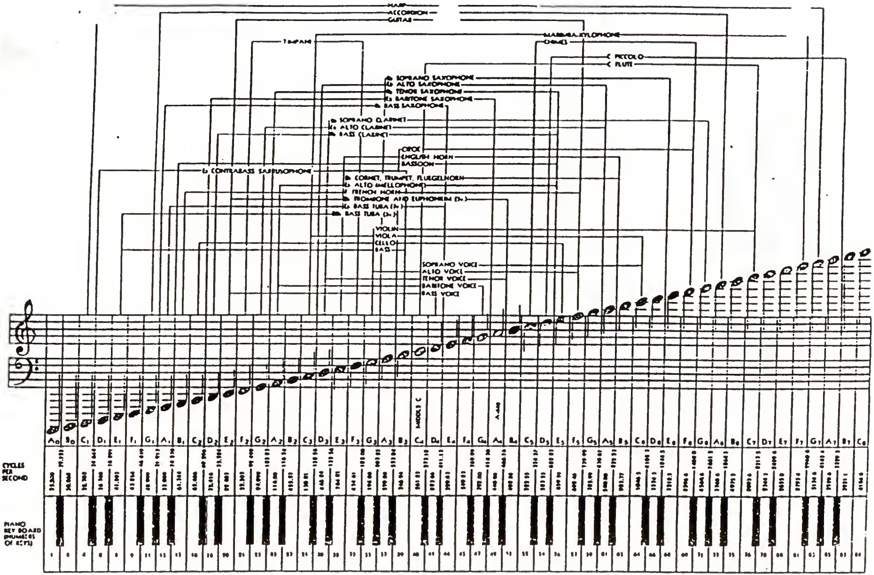


Chart showing the frequency range of the voice and various musical instruments. (C. G. Conn, Ltd.)

APPENDIX E
WITHIN SUBJECT EFFECTS OF VOCAL TRAINING ON THE SINGING VOICE

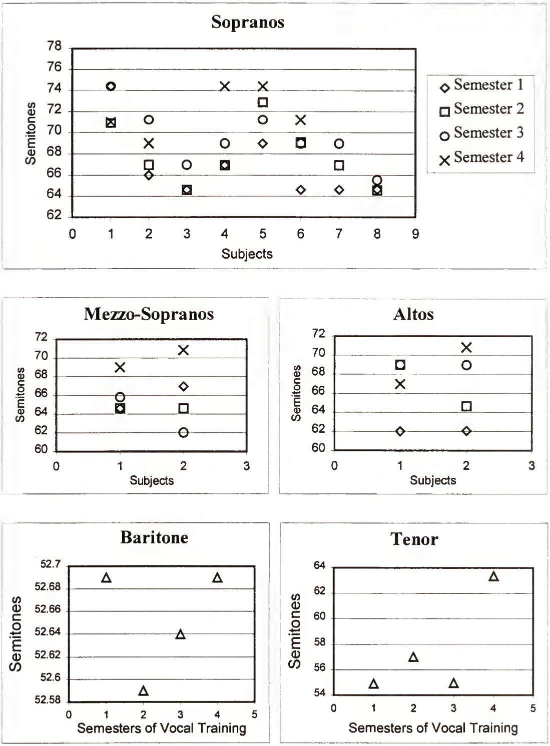


Figure E-1. Within subject changes of $F_0 90$ variable.

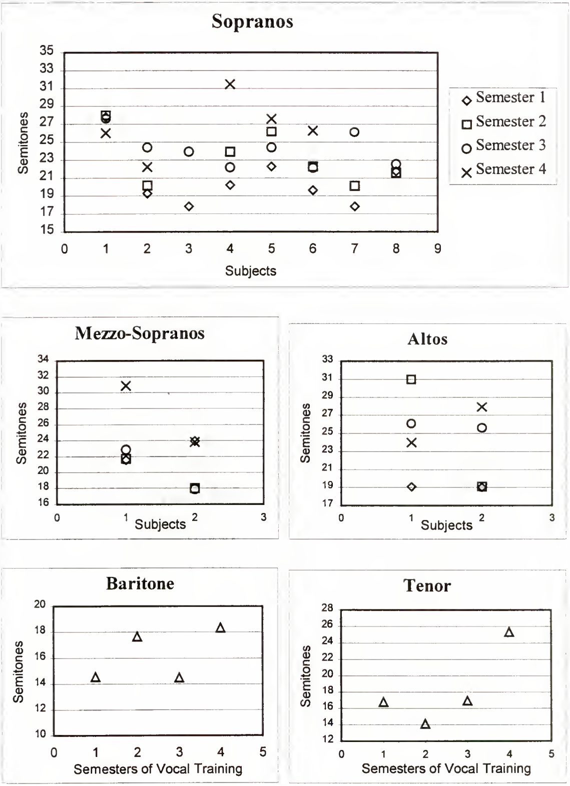


Figure E-2. Within subject changes of $F_0$90-10 variable.

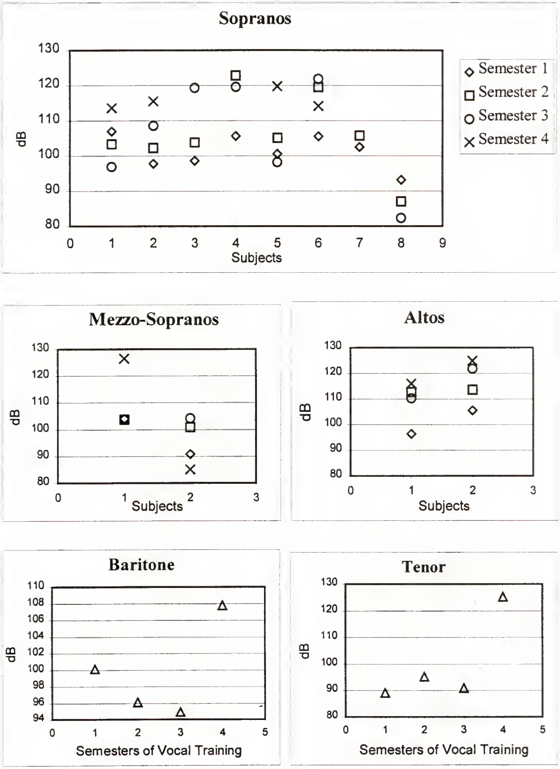


Figure E-3. Within subject changes of SPL90 variable.

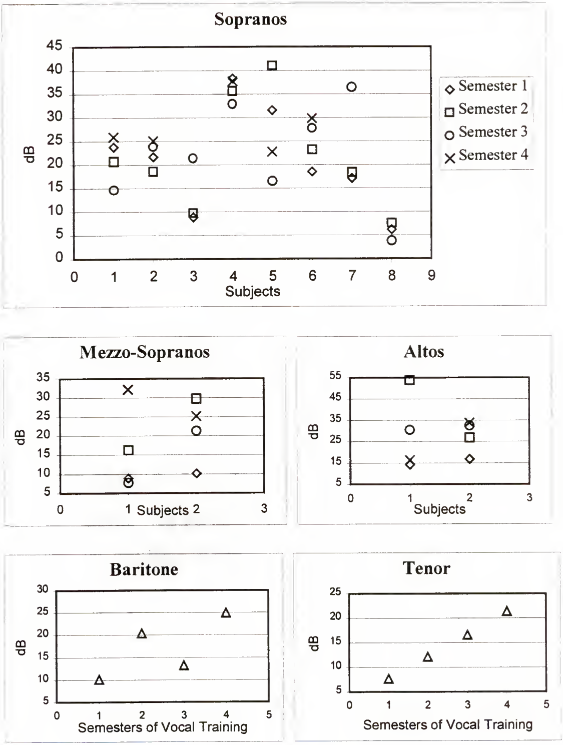


Figure E-4. Within subject changes of SPL90-10 variable.

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BIOGRAPHICAL SKETCH

Ana Paula de Brito Garcia Mendes was born in Lisbon, Portugal, on February 4, 1965. She spent three years at the Health Superior School of Alcoitao, where she obtained her bachelor's degree in speech therapy. She worked three years in an ENT hospital setting, where she organized and managed the Speech Disorders Department. In 1991, she was awarded the Rotary Scholarship to pursue her master's degree in speech-language pathology at Lehman College-CUNY. In 1995, she was a fully licensed and certified speech-language pathologist by the American Speech-Hearing Association. Also in 1995, she entered the Ph.D. program in the Department of Communication Sciences and Disorders at the University of Florida. During her doctoral studies, she was also awarded the Calouste Gulbenkian Scholarship. Her Doctor of Philosophy degree in Speech Science was awarded in 1999.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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